MIT/ DRAPER Technology Development Partnership Project:

Design, Assembly, and Test of the Launch and Flight Support and Deployment System for a Gun Launched Reconnaissance Vehicle

by

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Submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of
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Abstract

The MIT/ Draper Technology Development Partnership Project is a two year design and development project between Draper Laboratory and the MIT Department of Aeronautics and Astronautics. Overall aims of the project include the development and testing of an innovative first-of-a-kind system using the capabilities of both institutions over a two year period. During the first year, the Partnership decided on the design and development of a gun-launched aerial reconnaissance vehicle compatible with current U.S. Navy five inch guns. The second year team began with a review of the previous work and continued project development with the detailed design, manufacturing, and testing of two proof-of-concept vehicles.

This thesis reviews the system design from concept review through the final design and testing. Design and development of the launch and flight support system and the vehicle deployment system is covered in detail. These systems protect the reconnaissance flyer during launch and ballistic flight and initiate the deployment sequence. The major systems critical to a gun launched reconnaissance vehicle were tested. Innovative subsystems successfully survived launch within an eight inch test canister. The thesis covers the results of the development and testing and can serve as a design path for further integration and design of the vehicle into an operational unit.

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1.0 Introduction

1.1 MIT/Draper Technology Development Partnership Project

MIT/ Draper Technology Development Partnership Project is a program that seeks cooperation between Charles Stark Draper Laboratory and the Massachusetts Institute of Technology's Department of Aeronautics and Astronautics. A major goal of the program is to develop an innovative system to fulfill a national need and be capable of designing, building, and testing the system in a time span of two years. Objectives for the project emphasize "unobtainium," meaning a unique technology or system that has never been fully explored, tested, or developed. Preliminary work in the first year involved researching and identifying national needs, finding opportunity areas, performing market research and analysis, and identifying needs with potentially innovative or challenging solutions. This research and a project down-select led to the identification and selection of the Wide Area Surveillance Projectile (WASP). The WASP is a first-of-a-kind unmanned aerial vehicle system designed to provide real-time aerial coverage of a pre-selected area.

1.1.1 Program Objectives

Systems engineering education and skill development and Draper's challenge to develop a first-of-a-kind were the two main objectives of the MIT/ Draper Partnership. The MIT Aero/ Astro Master of Engineering (M. Eng.) program focuses on learning team design and systems engineering skills. A structured class schedule and team design experience with the Draper project provide a hands-on learning environment. The Draper project focuses on the development of an unprecedented system design involving innovation or technology application. Draper funds the project and is recognized as the system customer, with whom project requirements are developed and revised. Ultimately the system will have actual customers who will purchase and use the WASP system, and the design team was careful to meet the objectives of the final qualified system. Objectives of the project are to:

1. Develop a first-of-a-kind system
2. Provide a solution to a national problem, opportunity, or need

3. Involve "high-risk" technologies, termed "unobtainium"
4. Use integrated, multi-discipline product development techniques
5. Take advantage of enabling technologies
6. Be applicable to several markets and customer needs

1.1.2 Program Schedule – The Two Year Plan

The MIT/ Draper project began in the fall of 1996 and ended in the summer of 1998. Two teams of students contributed to the project, with three students present for the entire two years. Figures 1.1 and 1.2 contain the initial long-term schedule, which lists the project milestones and deadlines. First research was done to identify and categorize national needs, market niches, and possible areas for new technology development. Following this research and preliminary analyses five possible project ideas were formulated by the student team. From these five projects Draper chose to pursue a gun-launched reconnaissance vehicle that would provide fast response time at low cost, satisfying this national need identified by the team's research. The team began the preliminary design for a reconnaissance vehicle that was launched by typical guns of the U.S. armed forces. The project came to be known the Wide Area Surveillance Projectile, although the sole usage of the term surveillance is misleading, since reconnaissance is the primary focus of the system. The first year efforts produced documentation of national needs, market projections, a conceptual design for the vehicle, and an understanding of the analysis needed and challenges involved.

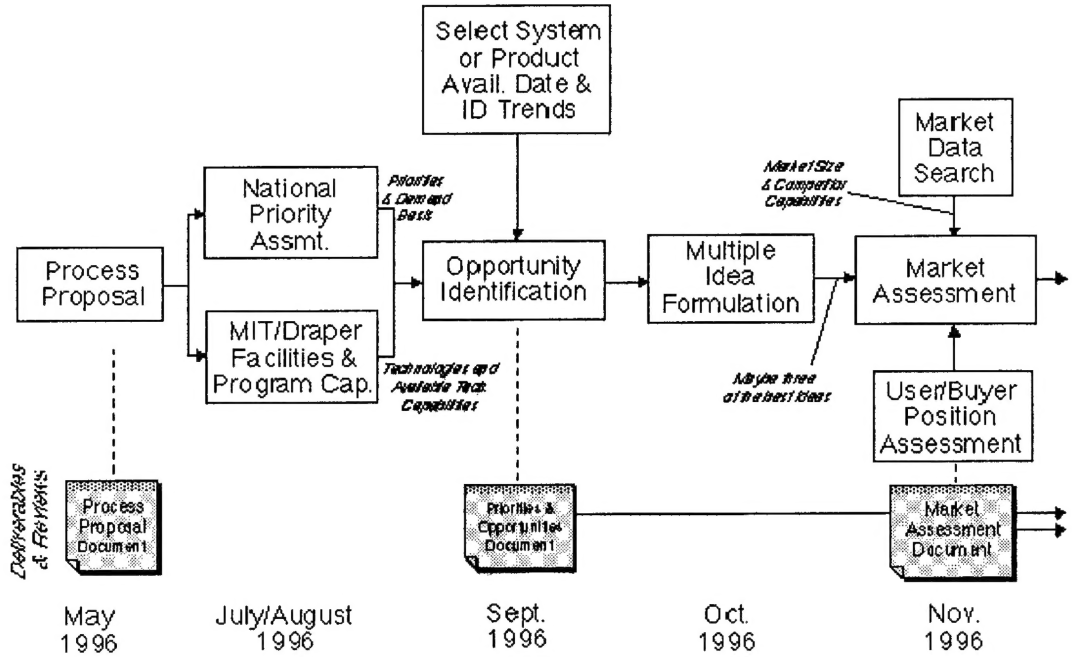


Figure 1.1: Two-Year MIT/ Draper Project Plan, May to November 1996

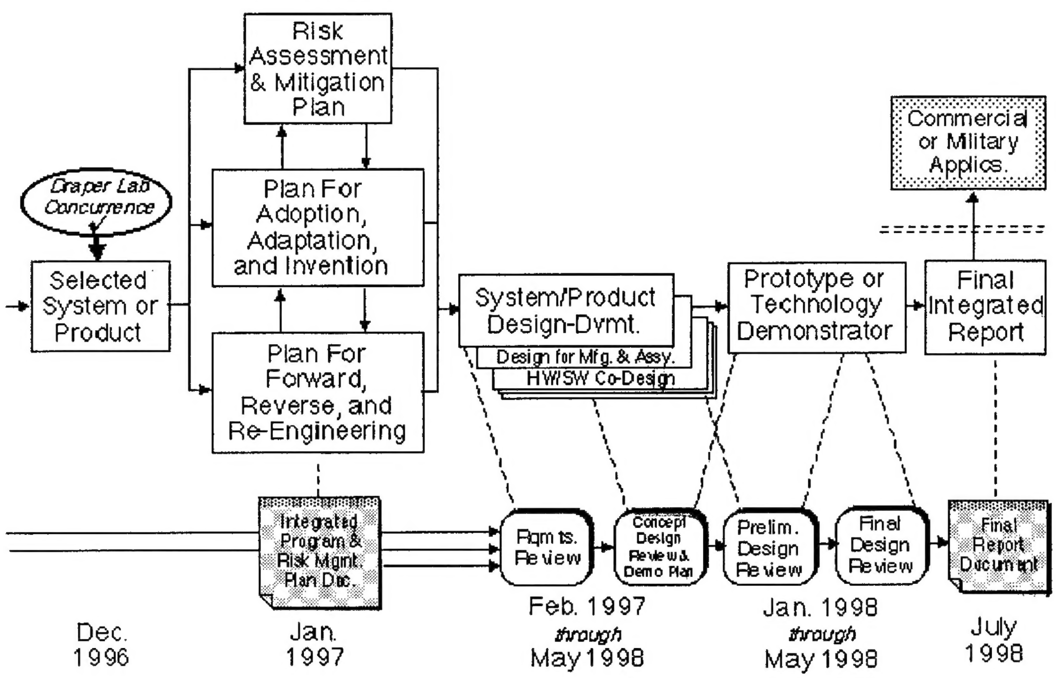


Figure 1.2: Two-Year MIT/ Draper Project Plan, December 1996 to July 1998

Many of the first year student team members finished their degrees in May 1997. Design work for the WASP by the second year team began in earnest in June 1997. Only three of the original members of the first year team continued through the entire second year. Two other members of the original team were able to continue for the majority of the summer. Two additional members joined the team in the fall of 1997, and the project continued through the rest of the design process and into the testing and verification stages. This thesis and those of the other team members referenced herein cover the work completed during this period and the technology demonstrations the team accomplished. The design of the WASP's launch protection, flight support, and deployment systems is covered in this thesis.

1.1.3 Mission Scenario

The WASP system is primarily designed to perform reconnaissance over a pre-selected target area. The mission concept recognizes the advantages of unmanned aerial vehicles (UAVs) for reconnaissance usage. WASP is designed to be a low-cost, fast response UAV that can be fired and controlled by smaller units with access to off-shore naval guns or army artillery. Range is an important factor in the performance of the system since a greater vehicle range will allow the gun to be stationed further from the area to be observed and thus safer. In combination with other projects under development at Draper and other laboratories, WASP can be used to gather information on missile or vehicle locations or assess battle damage, as shown in Figure 1.3. Other mission scenarios, such as long duration missions for area surveillance, communications relay, signal intelligence, or company-level reconnaissance have been proposed for the WASP system.

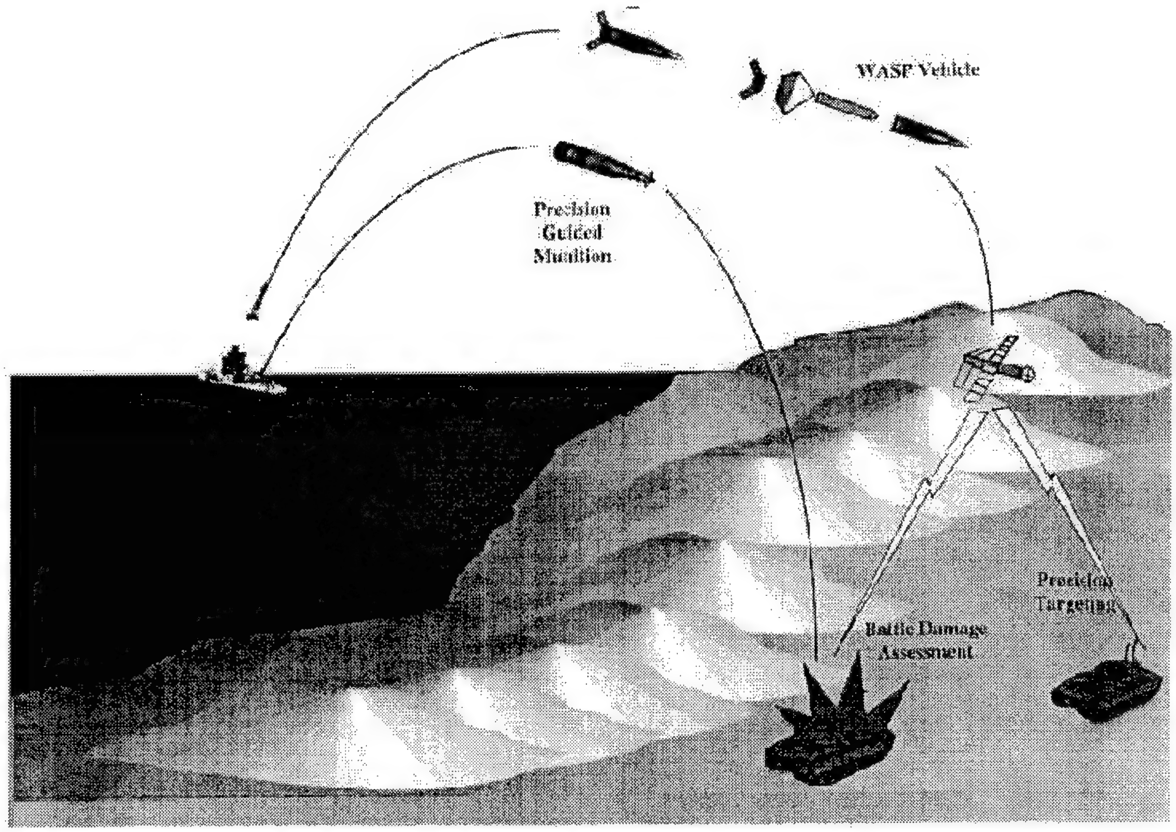


Figure 1.3: WASP Mission Scenario

1.1.4 System Requirements

Requirements for the WASP system were determined by consultations between Draper and the design team during the first year of the program. An effort was made to analyze initial customer requirements and goals for the system and produce a revised set of system requirements to meet the project objectives. From the revised customer requirements a set of weighted requirements for design development were determined. Table 1.1 below summarizes the system requirements and development process, providing an overall view of the system development goals and design requirements presented to the group of students that joined the project at the start of the second year. Detailed requirements development and analysis is covered in the first year documentation [1-5].

Table 1.1: System Requirement Development

Area	Initial Customer Requirements	Revised Customer Requirements	Related Requirements, Weighted 1-10
Launch	Navy 5", Army 155 mm Guns	same	high reliability (8), short launch time (3)
Range	70 - 200 miles	15 - 20 miles ballistically	long range (5),
Mission Time	1-8 hours	20 - 30 minutes	long loiter time (10),
Operational Time	2 hours	20 - 30 minutes	long operational time (10), ease of operations (10), long shelf life (4)
Imaging	camera	camera, 1 mile resolution	accurate positioning (9), max. field of view(8), max image resolution (8)
Information TIming	Near-real-time	1 image every 3-10 min.	Near-real-time (9),
Autonomous Operation	Some degree	same	high degree of autonomy (8), high reliability (8)
Cost	$20,000 - $30,000 per flight vehicle	$2,000 - $3,000 per flight vehicle	low cost (10)
Safety	Self-destruct, 8 oz. pieces	same	very safe to handle (10), minimal self-destruct debris (4)

1.1.5 WASP Market Niche

An important goal of the project was to produce a concept that could be marketed. There are many existing UAV systems that can perform reconnaissance missions. WASP had to offer advantages over the other UAVs on the market that would convince a prospective customer to purchase and use the system. The major advantages of this system were identified during the first year to be: 1) fast response time, 2) an ability to command the system by smaller units, and 3) low cost. A comparison of the vehicle and these advantages is shown schematically in Figure 1.4.

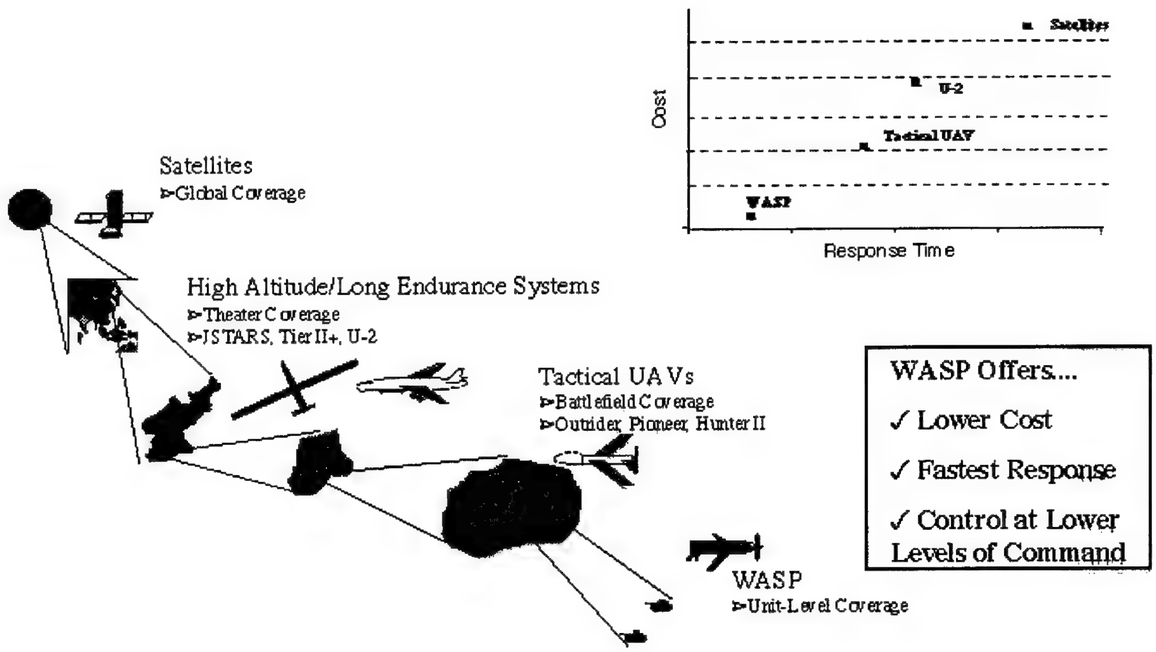


Figure 1.4: WASP Market Niche

1.1.6 Previous Work

Theses of the first year students [1-5] document the work performed prior to the integration and start of the second year team. Previous work in the structural aspects of the WASP flight support system was done by Cory R.A. Hallam [1]. At the time, the emphasis was to develop an entirely new shell made of composite material. Therefore much of the previous researcher's work refers to this design concept.

Work had developed to the point where the first year team had a conceptual design of the WASP system but no tests or reviews by persons knowledgeable in the design of gun-launched systems had been performed. Due to the complexity of the concept and the difficulty of testing an operational vehicle in the time allotted, the team decided to divide concept demonstration into two vehicles, as shown in Figure 1.5. Complete design of the operational vehicle would require state-of-the-art electronics technology due to the size and load constraints. The electronics would be expensive, and testing a fully operational vehicle would risk losing or destroying the electronics. The separation of the vehicles allowed the team to focus on specific challenges for each vehicle while demonstrating the viability of the WASP system.

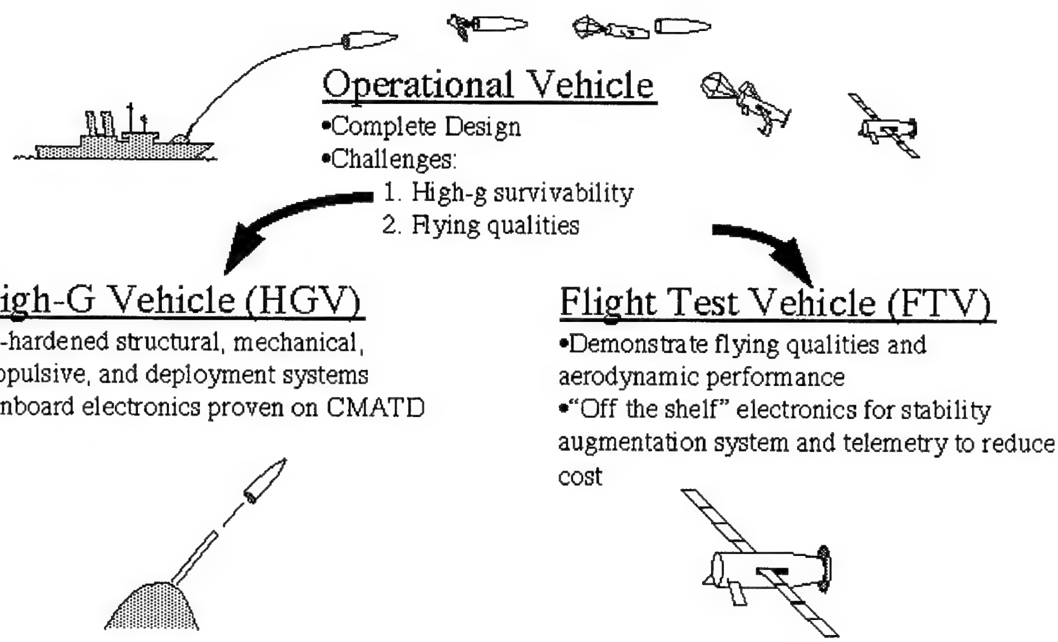


Figure 1.5: Concept Demonstration Schematic

Together the two vehicles test many of the "unobtainium" challenges associated with the design of a fully functional operational vehicle. As shown above, one vehicle would focus on the survivability of the vehicle when exposed to the high acceleration forces (hereafter referred to as the "high-g" environment) during launch. Termed the High-G Vehicle (HGV), it would replicate the structure of the operational vehicle and be able to test the mission sequence from gun launch to flyer deployment. The Flight Test Vehicle (FTV) would simulate the performance and handling qualities for the operational vehicle by using a scaled up version of the dimensions and configuration of the operational flyer. Autonomous control and navigation would be incorporated into the FTV using commercial, non-high-g qualified electronics making it cheaper, easier to build, and reducing development risk. Incorporating space for smaller, high-g qualified electronics in the HGV but not installing them would focus HGV testing on the structural aspects of the vehicle design without putting expensive electronics at risk. A set of Test Vehicle Requirements was generated and used to guide the system design process. Appendix A contains the Test Vehicle Requirements as stated at the start of the second year design phase.

The majority of the material covered within refers to the High-G Test Vehicle only, since it is the primary mission of this vehicle to prove the survivability of the system during launch, down-range flight, and deployment. It was also the goal of the High-G team to produce a test

vehicle close to the operational configuration of the WASP, and to verify more than just the survivability of the structure. Combining the operation of small, high-g qualified electronics modeled by the FTV into the structure of the HGV would produce a system capable of meeting the national need identified by the team for a fast response, inexpensive reconnaissance vehicle.

1.1.7 Initial Systems Concept

The leading concept at the conclusion of the first year was selected from four initial vehicle concepts developed during the spring of 1997. These four concepts are discussed in greater detail in Reference [1]. Small groups were formed where each was responsible for the concept research and evaluation. Initial dimensioning, layout, and structural analysis was performed for each concept. The chosen design was termed the "Supershell" and consisted of a fully integrated system, with a composite flyer body inserted directly into the gun and launched. The vehicle would be launched as a projectile and transform into a flyer following the ballistic flight. These stages are pictured below in Figure 1.6.

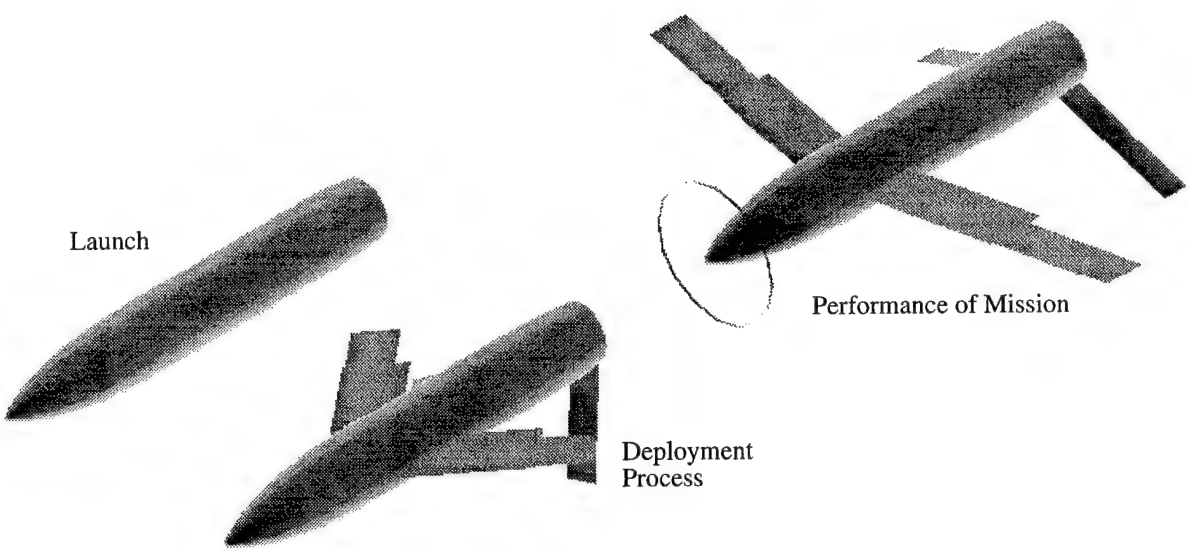


Figure 1.6: The Supershell Concept

Slots in the body would allow deployment of the wings, tails, and propeller blades. Other holes in the structure would be necessary for reconnaissance instruments, antennas, and cameras. The entire body would be constructed of composite material to reduce the weight of the flyer and pro-

vide better aerodynamic flight performance. The major dimensions of the Supershell are shown in Figure 1.7 and the inboard profile in Figure 1.8.

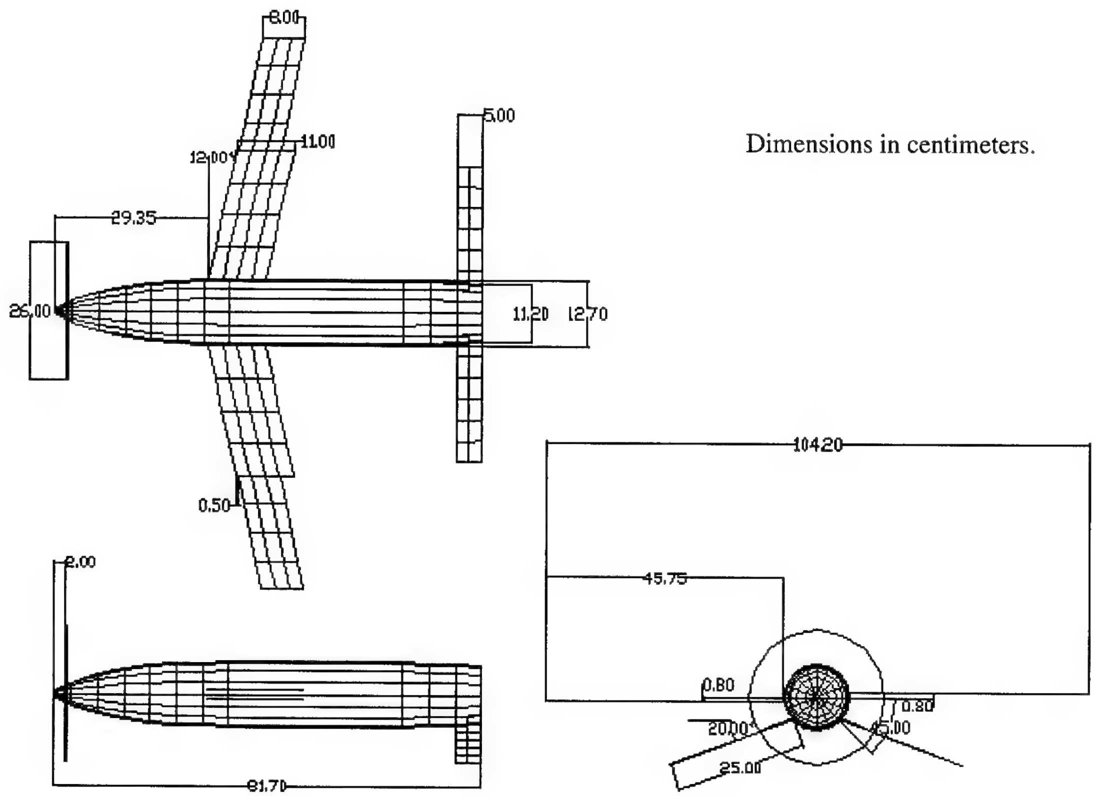


Figure 1.7: Supershell Vehicle Dimensions

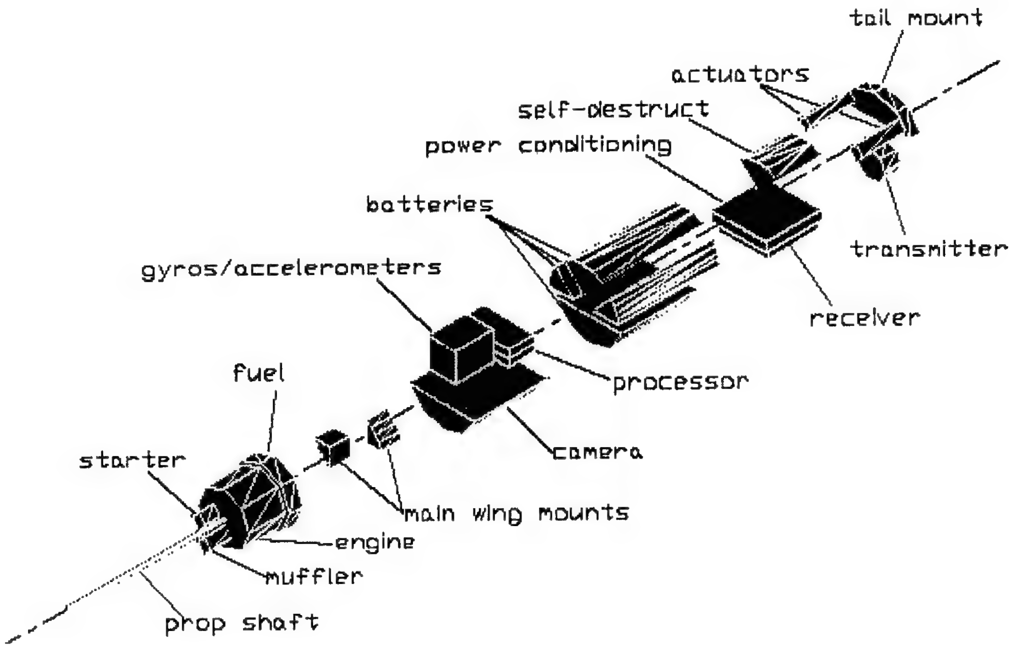


Figure 1.8: Supershell Component Layout

2.0 Preliminary Design and Concept Reevaluation

The first duty of the second year team was to become familiar with the project development and the work done the previous year. As the work was reviewed, many team members became aware of unforeseen challenges and difficulties of developing the Supershell concept. Designing Supershell would mean developing a composite projectile, currently an ongoing project in government research facilities, and still considered a new application area for composites. Therefore the team repeated the concept development and analysis process and developed a different approach using conventional shell designs. Concept analysis was augmented by consulting current experts in gun technology and conducting more detailed research into the gun environment.

2.1 Considerations

Many factors led the second year team to repeat the concept development and down-select process. Testing of the Supershell concept had still not begun and during the summer of the second team's arrival was consistently delayed. The second year team was excited by the concept yet

felt that the design was risky and difficult to validate in the year remaining to complete the project. Detailed explanations of the reasons are given in the following sections.

2.1.1 Gun Environment

Projectiles launched from the standard 5" Navy gun have certain requirements and interfaces they must meet to be used by the fleet. These requirements were researched using available references and extensive conversations with Navy projectile suppliers at the Naval Surface Warfare Center Crane Division (Crane, Indiana) and projectile design engineers at the Naval Surface Warfare Center Dahlgren Division (Dahlgren, Virginia). Design requirements to be met can be considered in terms of the projectile launch sequence.

The first issue involves handling and preparation of the projectile for launch. Navy guns use automatic loading systems which require certain dimensions and features to be located on each projectile. Projectiles must be certain lengths or fit certain geometries to avoid automatic loading shut down. Forward areas of the projectile must have a groove by which the auto-loader grasps the shell as it is selected and loaded. Propellant containers are placed behind the projectile and the entire load is rammed into the breech of the gun in one motion. The shell must be sturdy at its base to withstand the force of the mounting ram.

Correct placement of the projectile within the gun is determined by the obturator position. An obturator is a band of material around projectiles with an outer diameter greater than the gun barrel. Obturators serve multiple functions; they halt the projectile at the correct location in the gun breach, provide a seal between the barrel wall and the projectile, and interact with the barrel rifling. Correct location ensures the obturator seals the breach as designed, which is important to prevent "blow-by" during launch. Blow-by occurs when the seal between the projectile and gun is not complete, and the pressure in the breach is released around the projectile. Combustion gases flow around the projectile without accelerating it to the correct speeds. In spin-stabilized projectiles, the obturators retain the seal while engaging the barrel rifling. Rifling refers to the spiral grooves cut into the gun barrel interior that impart spin to the shell as its accelerated. In fin-stabilized projectiles, the obturator is designed to provide only the seal and not to engage the rifling. Usually made of nylon, these "slip-obturators" are not sturdy enough to remain engaged

in the rifling, and impart very little spin. Obturators are a necessary component in any projectile fired from a rifled gun.

Launch involves high pressures exerted on all parts of the body, large inertial accelerations, and exposure to heat and large vibration levels. These effects occur over time periods of milliseconds, causing large impulsive stresses and stress waves in the projectile that are difficult to model analytically [6]. Standard weight projectiles undergo accelerations on the order of 12,000 times the force of gravity (referred to as g's) from the aft pressure forces. Motion of the projectile down the barrel results in balloting, side-to-side knocking of the projectile within the barrel cylinder. Balloting can result in lateral accelerations on the order of one thousand g's and is imparted to raised bumps of material on the outside of the projectile body.

Projectile barrel exit releases the pressure forces on the body almost instantaneously. Acceleration of the projectile has put energy into the system that is free to be released when the energy build-up is finished. Structural compression of the projectile occurs due to the high g-load from the aft pressure. The release of the compression force causes the projectile to release the energy by "springing" back into its original shape. This effect results in a reverse acceleration of up to one-third the initial g-load: estimated at 4,000 g's for standard weight projectiles. Termed rebound, the effect can cause systems designed solely for the forward acceleration to fail suddenly as they exit the barrel. Characterization of rebound forces was revealed to the team by contacts at the Dahlgren Navy facility [7].

2.1.2 Schedule

Development time for a new projectile is nominally given in years, and current government facilities were pursuing composite projectile and gun designs. With one year already past, and no analytical or test results for a composite shell completed, successful development was highly unlikely. Efforts to build and test composite cylinders to simulate a shell structure were constantly delayed by problems in manufacturing composites and the lack of resources to test models at full scale. There was no reason to believe the MIT/ Draper team could reduce the nominal time estimate. Therefore the team returned to concept development with more details of shell

design available through professional contacts and a need to find existing components that could be used to meet the WASP requirements.

2.1.3 Projectile Design Risk

Development of an entirely new projectile is a significant task, especially when using non-conventional materials such as composites. These risks were first revealed while talking with gun experts at Picatinny Arsenal [8] who have had experience working with structural design for gun-launched vehicles and composites. Current projectile technology dates to the Second World War, and exact loading conditions and behavior cannot be modeled completely. Most projectiles use steel as the structural material for the projectile outer wall, referred to as the shell. Shell design is seen by many within the field as "black art" using design tools and knowledge based on experience and rigorous field testing. Mean time for new projectile development was given in years with extensive field testing in actual guns, a development far beyond the scope and abilities of the current project. New projectile designs must pass through a rigorous testing and qualification procedure prior to use in the Navy fleet or Army arsenal. A system incorporating a flying vehicle that took advantage of current projectile designs would reduce development risk and design time. The closer the shell system was to current proven technology, the less risk associated with the design and development of the WASP vehicle.

There was a knowledge base within Draper Laboratories concerning current projectile alterations and design changes. Draper has been involved with the Smart Munitions Program, the development of the Extended Range Guided Munition navigation unit, and an Advanced Technology Demonstration (ATD) of a guided round. The ATD involves extensive alterations to the current standard Navy projectile, the Mark 64, used in unguided explosive artillery shells. Alterations included cutting the projectile in half, removing material from within the shell, replacing areas with different materials, and reassembling the projectile to provide more interior volume. Extensive analysis determined the design limits that would retain structural integrity. For example, a minimum shell wall thickness was necessary to ensure survival during forward acceleration. The difficulty inherent in analyzing and developing a new projectile design from composites was stressed by naval gun experts and designers at Draper. Composites have a higher strength to weight ratio than metals, the primary advantage over steel projectiles. They are much harder to

analyze, fast computer analysis programs are rare, and models for composite reactions to similar loads are not widely available. The knowledge base and methods of analysis necessary to fully develop a new composite shell were not present, and convenient testing options were not available for large-scale models. According to personnel at Dahlgren, worthwhile composite projectile testing must be done with full-scale models to get useful data on material behavior [7]. The consensus was that composites could be considered for future designs but not until they are qualified by experienced projectile designers and used in the field.

Due to the above reasoning, the team repeated the concept generation and down select process. This process led to a different conclusion that proved simpler to implement and design in the long term, and more likely to be successful adapting to current gun technology.

2.2 Concept Proposals

Different concepts of how to accomplish the mission were developed within a smaller team in the first month. Concept development was based on what the team had researched about the system, the information contained in the theses from the previous year, and information from reference sources and field experts. The guidelines based on this information are briefly reviewed prior to detailed explanation of the vehicle concepts.

2.2.1 Concept Development Guidelines

Issues the team kept in mind during concept development determined the focus and direction of the process. Eight guidelines were developed to help evaluate the concepts. Due to the schedule limitations, each design was judged on the design and manufacturing complexity. The team was aware of a moderate level of complexity regardless of the concept but felt it important to differentiate even further to avoid choosing a concept that would later prove difficult to manufacture or design. These judgements were based on the experience of team members and the advice of experienced professionals. With only one year remaining, a simpler vehicle design and faster manufacturing would allow the team to accomplish the project goals and perhaps more.

Range of the vehicle was also an important factor for concept development. Research during the project's first year [1] demonstrated that the best possible range was achieved with a five inch projectile weighing close to 77 pounds, much too heavy to perform as a flyer. Longer ranges

would make the vehicle more attractive to potential customers since the gun could be located farther away from the reconnaissance area, where potential adversaries could be located. To fulfill the mission scenario shown in Figure 1.3, the vehicle would require a range of fifteen nautical miles, close to that of current artillery shells [9]. The projected light weight of the Supershell would result in a reduced range in comparison to heavier shells of similar size, reducing the effectiveness of the WASP vehicle.

Launch survival of the flyer, termed vehicle protection, was a high design priority. WASP is useless unless it can survive launch with all vital systems functioning and successfully perform a given mission. Launch is the first challenge to system functionality, and is the most likely point at which components fail. Launch accelerations represent loads of several thousands times the vehicle weight. Research demonstrated that since the force input of the propellant is predetermined, the g-load increases for lightweight projectiles due to simple physics: force equals mass times acceleration. This was another negative for the Supershell design- for good flight performance as an integral flyer and projectile the vehicle would have to be lightweight, resulting in increased acceleration loads. An ideal system could be launched at standard projectile weight and g-load to reduce launch loads but then release or remove mass to retain performance as a flyer.

Another important measure of performance for the WASP is the loiter time. Loiter time is defined as the amount of time the flyer can remain aloft performing the reconnaissance mission. It is a function of the amount of fuel on board, engine efficiency, aerodynamic performance, and weight. These requirements relate to vehicle volume, engine selection, overall design, and projected weight- so each concept attempted to provide the best options in these areas.

Regardless of design, the vehicle must remain stable following gun launch. Standard naval and artillery guns use rifling to produce spin. Mark 64 projectile obturators, for example, engage these grooves and spin the projectiles for a stable ballistic flight to the target. Due to placement and component constraints, the favored stabilization method for concept generation was fin stabilization. Methods to prevent spinning due to interaction with rifled gun barrels do exist but are limited in application. Preferred concepts could incorporate a method that would avoid spinning the assembly. Spin-stabilization remained a back-up alternative for ballistic stability.

The flyer was required to contain the necessary electronics and flight surfaces to control its flight and perform the reconnaissance mission. These components would all require a certain

internal volume and a structure that could support the weight of the entire assembly. Each concept was judged on the internal volume that would likely be available, with higher volume concepts preferred.

Consistent with the operational launch procedure, each concept was evaluated based on the gun automatic loading interface. Current Navy guns use an automatic loading system that processes twenty rounds each minute. The automatic gun mount requires a location at the nose of the projectile for the mount to hold and orient the projectile prior to insertion into the barrel. Each concept was judged on whether this interface could be incorporated.

2.2.2 Concepts

Four concepts were proposed for review by the student team, professors, and field experts. Use of composites was not rejected outright due to the improved strength to weight ratio and the efforts and experience of team members in this area. Vehicle functionality and limitations on development time were the driving factors behind the concept development.

Concept One used a sabot to interface with the gun barrel and launch gases. Sabots are separate components that protect a projectile by isolating the vehicle from the rifled barrel and absorbing the pressures of launch while imparting acceleration. They are usually discarded immediately following barrel exit. Sabots are used mostly for unguided kinetic projectiles [10, 11]. A conceptual design is shown in Figure 2.1 below.

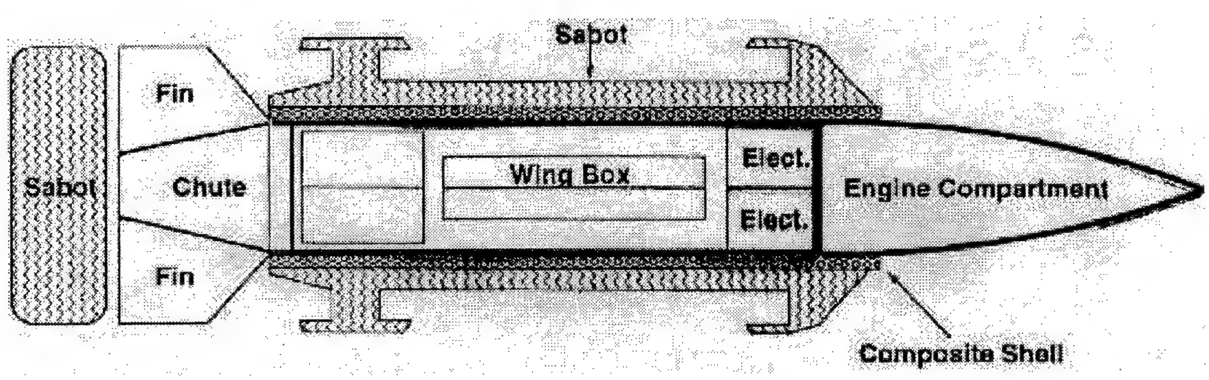


Figure 2.1: Concept One- Sabot Supported Vehicle

The second concept considered was a composite/metal combination that attempted to use the best attributes of each material. Metal surrounds the flyer configuration where the launch gases are encountered and where the forward end would interface with the barrel. Launch loads and interior components would be supported by the internal structure. The composite would serve as a lightweight skin for the flyer and would not interact with the gun barrel. A conceptual view is shown in Figure 2.2.

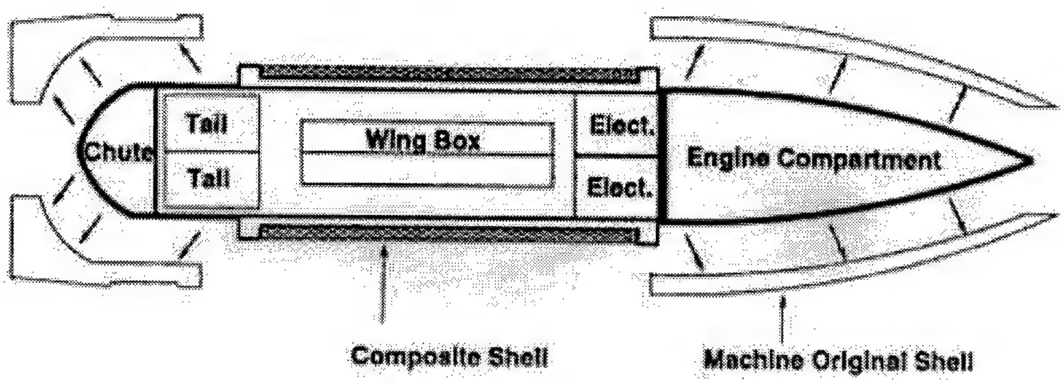


Figure 2.2: Concept Two- Composite/ Metal Shell and Flyer

Concept Three, termed the Shell-Contained Flyer, used a modified Mark 64 shell to contain and support the flyer. An outer metal support structure would interface with the rifled barrel and provide all of the structural support during launch. It would enclose the flyer, which could be surrounded by a thin composite skin to provide internal support and a smooth aerodynamic surface. This shell would be discarded from the vehicle after ballistic flight to the range needed, deploying the enclosed flyer to perform the mission. Concept Three was the only concept to completely separate the flyer from a shell that supports launch and ballistic flight. A schematic used to illustrate the concept is shown in Figure 2.3.

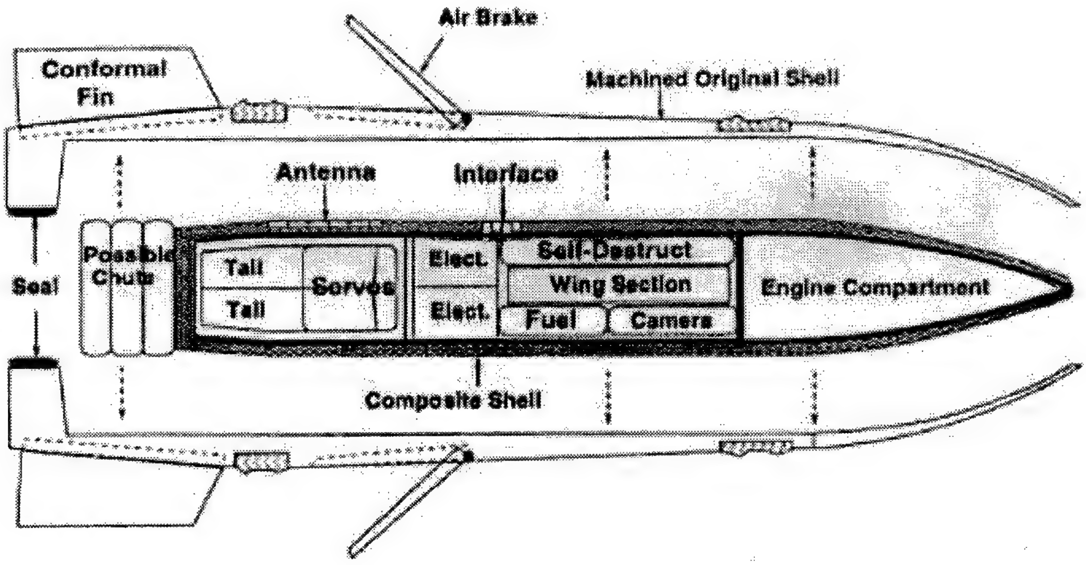


Figure 2.3: Concept Three- Shell Contained Flyer

The final concept was similar to Supershell in that it combined the flyer and shell into one complete vehicle. Concept Four supported itself during launch and transformed into a flyer after flying down range. Vehicle surfaces would interface with the gun barrel, support the internal components during launch loads, and serve as the aerodynamic skin. This concept matched the original idea except for the metal shell. Therefore the concept was altered to include the original proposal of an all-in-one shell and flyer, with both made of uniform material (composite or metal). A concept schematic is shown in Figure 2.4.

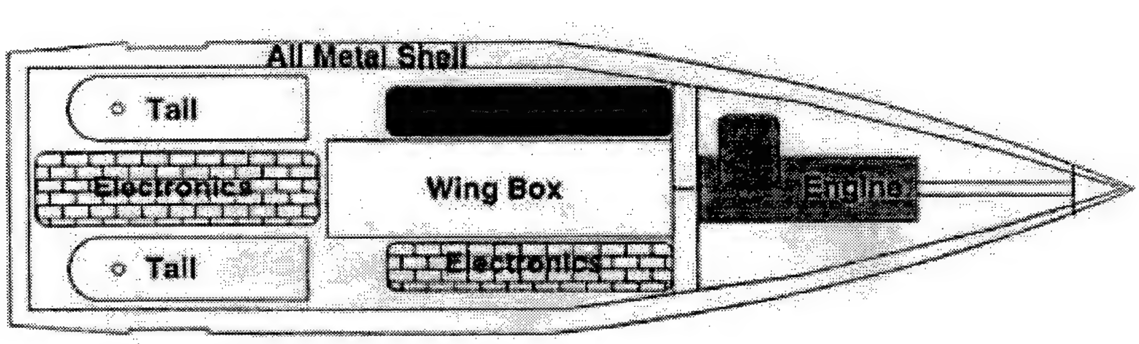


Figure 2.4: Concept Four- Shell/ Flyer, Uniform Structural Material

2.2.3 Conceptual Research and Design

The above concepts were further developed by comparing with current practice, laying out different configurations, analyzing first cut data, and using engineering judgement. As mentioned the majority of the sabot-launched vehicles are unguided kinetic projectiles. Sabot designs encountered were usually quite large, and for a five inch gun, this limited the internal volume of the flyer.

Although there was no precedent for Concept Two, it became clear from initial layouts that it would be difficult to attach and release the metal portions. Comparison of this concept with Concept Three did not reveal much benefit other than possibly a larger internal volume. Design and manufacture of this concept would be one of the more complex of the four concepts.

Contacts at Dahlgren believed that Concept Three would have difficulty to containing the load within the shell [12]. Citing the launch accelerations and the pressure on the base, the Dahlgren contacts considered the concept difficult to design. The comments went on to provide useful information and data for the parachute and gun designs. Engineering drawings of a round that could contain a payload within the projectile structure and was currently in development were sent to assist the design process. These drawings were the first drawings received of the illumination round discussed in later sections.

Concept Four limited the performance in some way regardless of the material used. An all-metal vehicle that could survive launch would be heavy as a flyer. The weight would reduce the loiter time and jeopardize successful performance of the mission. A composite vehicle would be much lighter, but this would limit performance in other ways. In general, lighter projectile systems have decreased range and are subject to higher acceleration forces at launch.

To determine the necessary internal volume, component sizes and weights were listed and updated as information on the exact electronics needed for the operational flyer were finalized. This process generated a list of necessary components regardless of the design choice and a total volume estimate for components and structure. The list was updated as the component selection and vehicle development progressed until the components and the concept choice were finalized. Appendix B contains the last updated list for the operational vehicle and the FTV.

2.2.4 Concept Evaluation and Down-Select

Weights were assigned to the above guidelines, and following some preliminary calculations, each concept was presented to the team. Initial judgement determined that Concept Three and Concept One were viable concepts, but that many of the criteria and weighting were not based on complete information, so a definitive choice was postponed until the team could research more details on current systems. Research focused on refining these concepts, searching for simpler alternatives, becoming more familiar with existing designs and systems, and attempting to analyze the concepts. Initial finite element analysis by Draper engineers for Concept Three determined a few constraints of the design such as minimum material thickness and load paths. The team decided to retain the composite Supershell as a concept.

The search for alternatives lead to research into cargo rounds. Cargo rounds refer to projectiles that carry a payload deployed from within the projectile body after launch. The most common type of cargo round is the illumination round, which contains an ejection charge, incendiary flare, a large descent parachute, and a deceleration chute. Current Navy illumination rounds use the Mark 48 Mod 1 projectile, similar in shape to the Mark 64 but with modifications that allow the illumination materials to be inserted into and extracted from the aft end. The projectile has parallel interior walls, a modified aft end and obturator placement, and a removable base plug. Figure 2.5 is a drawing of an illumination round, showing the major characteristics.

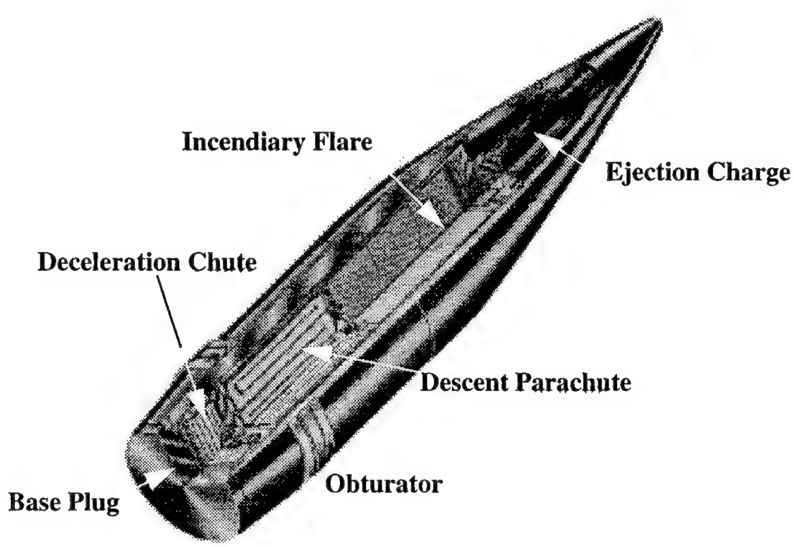


Figure 2.5: Illumination Round

The parachutes and flares are ejected out the back end of the shell, decelerated, and float slowly to the ground while the flare illuminates the surrounding area. It was quickly recognized that the illumination round performed many of the functions that Concept Three had hoped to accomplish. Similar in idea to Concept Three, the Shell Contained Flyer, the illumination round was an existing, proven system currently used by fleet and ground forces. Using the dimensions of the illuminating cargo [13], initial volume estimates matched those of Concept Three without having to modify the shell. After gathering more information on the deployment process, weight, and design, the team decided to pursue a vehicle based on the illumination round shell, and concluded overall concept development.

2.2.5 Illumination Round Characteristics

Design of the shell occurred many years ago. It was tested and developed without the benefit of extensive, detailed analysis available today. Dimensions of the projectile body are shown in detail in the part drawings received from NWSC Crane (Appendix D). In addition to the Mark 48 Mod 1 the Navy is developing a new illumination round with improved range, higher reliability, and a higher level of analysis used in the design process [14]. This round will eventually replace the current illumination round should its design prove successful.

The illumination round body follows the forward contours of the Mk 64 projectile body, except for the aft end. Changing the geometry of the aft end allows parallel walls throughout the length of the shell and extraction of cargo from the rear. It uses two obturator bands towards the rear instead of one to reduce the compressive circular load on the shell. Dahlgren personnel were not sure of the purpose of two obturator bands, but it is suspected that the forward obturator seals the breach while the rear obturator ensures correct seating [14]. Within the shell wall a step was placed at the rear. This allowed for insertion of a base with an interference fit between the first small step and the base diameter. A model of the body shown in Figure 2.6 was made to familiarize the team with the design and provide a base model to which modifications could be made. Pins were also inserted from the outside of the shell through the shell and base material. The interference fit and pins ensure support of the illumination round cargo within the shell during launch, rebound, and ballistic flight.

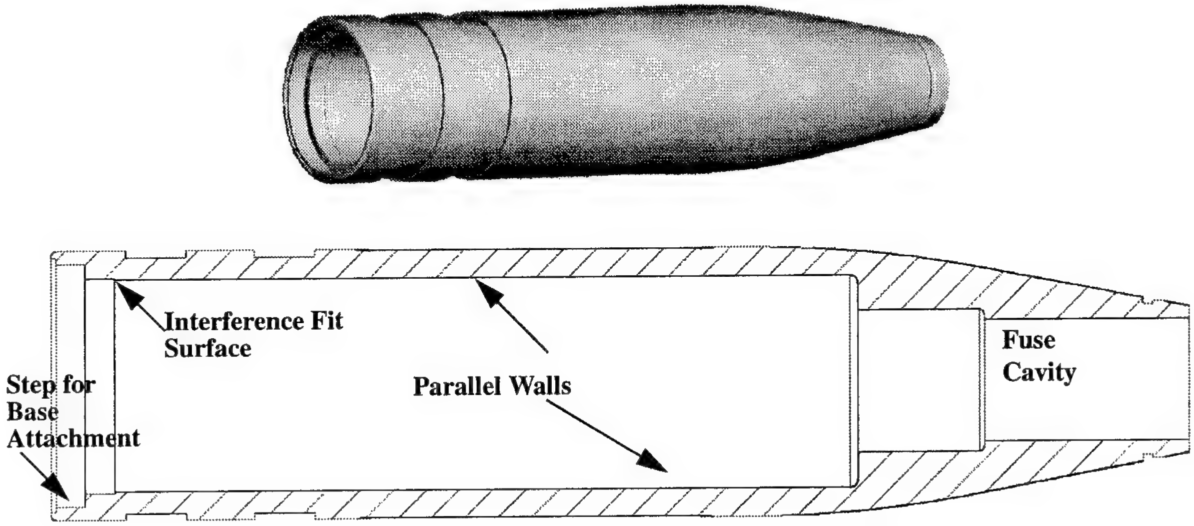


Figure 2.6: Model and Cross Section of Illumination Round Body

The nose of the shell consisted of the standard NATO fuse for illumination rounds. The fuse consists of a high-g switch and timer that are used to activate the deployment of the illumination round cargo. The fuse can be set by the auto-load systems currently in use by the Navy to match the specified gun angle, range, and required time to deployment. When the illumination round and shell are fully assembled, the fuse is screwed on, and the projectile is ready to be launched.

A high-g fuse switch, timer mechanism, and explosive charge are included within the nose fuse. The switch is activated by the high-g launch, which activates the timer to track the flight time of the projectile. Upon activation, the fuse ignites an explosive charge consisting of black powder in front of the illumination round cargo. The charge generates hot gases and pressure that travels along the outside of the illumination round canister and impinges on the base/ shell interface. Pressure forces are built quickly enough to eject the base from the rear of the shell. Counterweights cause the base to tumble out of the wake of the shell. A cord attached from the base to the Ram Air Inflatable Decelerator (RAID) drogue chute assists in rapidly deploying the chute behind the cargo and shell. The forces of the RAID cause the illumination cargo to be pulled from the interior of the shell and decelerated. After deceleration a large chute inflates and the illumination material ignites, allowing the bright incandescent flare to slowly drift to the ground. Reliabil-

ity of the illumination round is approximately 75%. Details of the illumination round operation were provided by personnel at the Naval Surface Warfare Center, Crane [15].

The range of the Mark 48 Mod 1 is comparable to that of Mark 64 explosive rounds. Due to the straight walls of the shell rear (no boat-tail) it produces a greater amount of drag than the explosive rounds. This results in a reduction of the range from 15 nautical miles for the explosive round to approximately 12 nautical miles for the illumination round. One goal of the WASP project is to reach the 15 nm point ballistically with no loss of coverage over the area in which its deployed. The range is a major factor in the current redesign of the round; by adding a tapered rear end to the shell (a boat-tail) and a hollow aft cavity the designers are hoping for more than 20 nautical miles. Successful development of this round and future integration with the flyer design could lead to greater vehicle range and better vehicle performance.

Base and shell attachments vary between that of the old illumination round and the new illumination round. The old illumination round uses an interference fit between the base and the shell of approximately 4 or 5 thousandths of an inch. Unfortunately the production of the base is not an exact process, and it is difficult to make each shell and base exactly. Therefore the base is marked corresponding to successful fit with a particular shell [16]. The base is placed beneath a hand press and are forced into the shell with a pressure up to 13 kpsi [17]. If the press reaches a higher pressure, the press operator halts the process and does not attempt to fit the base to that shell, but selects another. Some bases and shells are assembled with very little pressure. To make up for the variability between base and shell sizes, bases are also pinned. Pins are inserted through the shell exterior into the base, and are sheared when the explosive charge ejects the base. There are four pins inserted radially straight into the base and four pins inserted at a 45 degree angle [16]. These pins compensate for the variability within the production process of the base and shell.

This new illumination round design avoids variability in press fit processes. The new base design is attached to the shell with threads located on the inside rear of the shell. By reproducing exact thread specifications, variance of the production process is allowed to exist on the non-threaded initial production runs. Threads are specified to a particular diameter and size, simplifying assembly and allowing parts to be interchanged. Regardless of design, the decision to pursue the illumination round concept allowed detailed design of the vehicle to progress since many of the problems had been resolved.

3.0 System Design

System design includes the all components required for the successful performance of the mission. This includes not only the vehicle itself but ground hardware to operate flight control and receive information from the reconnaissance instruments. The entire operational system would consist of a launch-ready vehicle and a ground station to initialize and control the vehicle.

3.1 Overview

Initial design began with the dimensions of the illumination round cargo and a rough layout known. Information on the exact design and geometry of the projectile body was not immediately available. First to arrive were the engineering drawings for the new illumination round that was undergoing development at Dahlgren [12]. This shell was predicted to improve the performance of the projectile body, but had less internal volume. Due to the reduced volume and to avoid risking the design on the success of the new illumination round the team decided to proceed with the current projectile body. Detailed drawings that showed the dimensions and assembly were eventually received and integrated design of the flyer and projectile body proceeded. During this time the operational sequence, interfaces, and design guidelines necessary to accomplish the mission were determined.

3.1.1 System Design Interfaces

Much of the design process focused on the definition and solutions to the interfaces within the vehicle systems and the external interfaces with existing guns and hardware. System design required close interaction within the design team and between the team and outside resources to help define these interfaces and improve the vehicle design. Figure 3.1 is a schematic generated by the first year team presenting a good overview of the system interfaces.

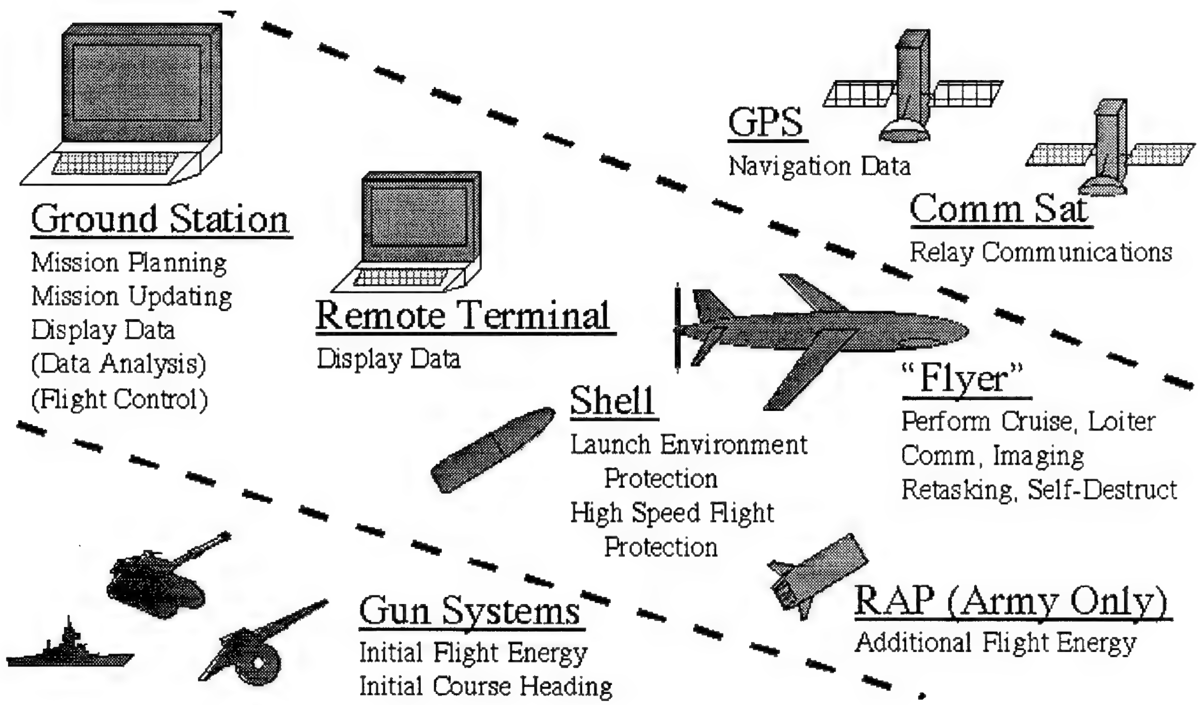


Figure 3.1: System Interfaces

3.1.2 Operational Sequence

WASP still lacked a definitive, detailed sequence of operation from gun launch to mission end. Lack of an overall mission profile hindered detailed design of a fully integrated system and led to some initial confusion within the design team. An operational sequence which listed the times, velocities, altitudes, component functions, and method of testing for each step from pre-launch to mission completion was generated, and is enclosed in Appendix C. The development of the operational sequence provided a baseline mission profile for the entire team and allowed detailed design to progress with the larger picture in mind. A summarized sequence is shown in Figure 3.2 below.

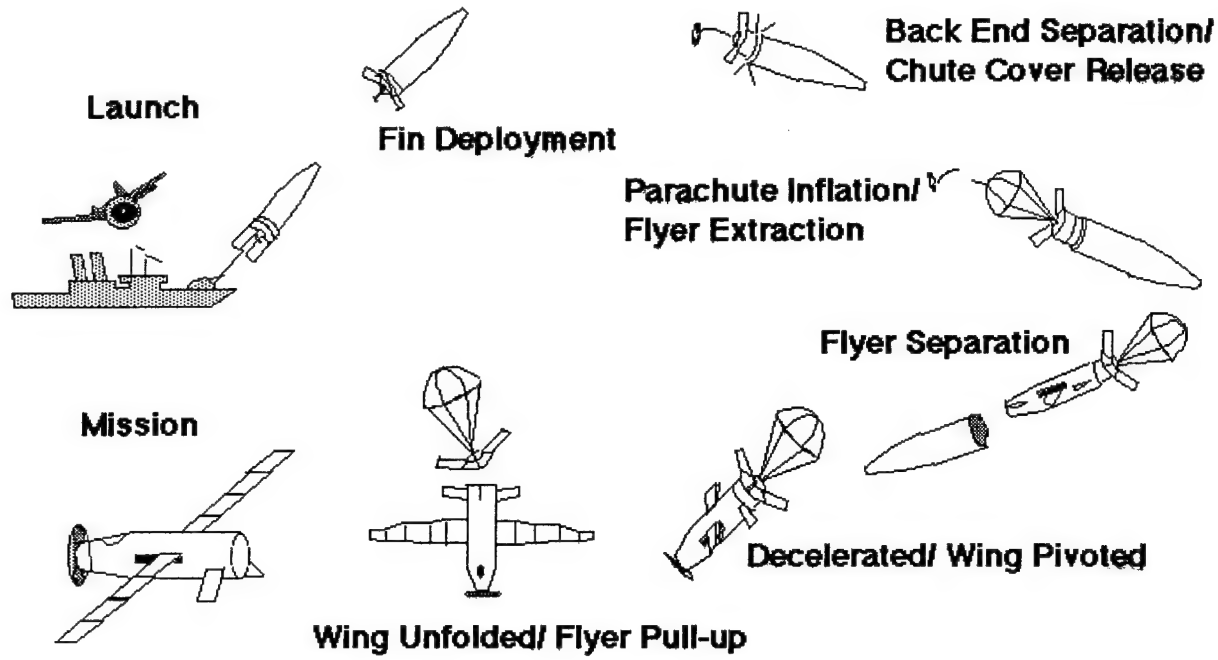


Figure 3.2: Operational Sequence of the WASP

3.1.3 Flight Test Vehicle

The Flight Test Vehicle was designed and built by members of the team with experience in control and aerodynamics. It is a 128% scaled model of the High-G Vehicle design. The deployed-wing profile was scaled up and made in solid halves of carbon fiber. The external structure matches the High-G Vehicle as closely as possible but is made of inexpensive, readily available materials such as sheet aluminum, aluminum tubing, and wood. Integration, functionality, and testing of the electronics was the most critical focus of the flight test vehicle. The electronic system provides autonomous operation unless commanded remotely by the ground station controls. The electronics were all commercially available components or constructed in house. The design is covered in further detail below.

3.1.4 High-G Test Vehicle

The purpose of the HGV was to test the structural integrity of the operational design under the conditions of launch and ballistic flight. As the project progressed, more emphasis was put on the HGV to test other aspects of the work beyond launch survival, such as the deployment

sequence, component functionality after deployment, and connections between electronic components. The ultimate goal of the HGV was to be shot from a 5" Naval gun and demonstrate complete functionality up to the mission start.

3.1.5 Ground Station

As part of the total product design a ground station with which to receive data and send commands to the vehicle was also developed. The ground station provides the capabilities to prepare, plan and carry out a mission and to receive the flyer reconnaissance data. It also provides an interface for a human controller to give the flyer commands and allow for mission updates or changes during flight. Design and integration of the ground station is covered in Reference [18].

3.1.6 Operational Vehicle

Complete operational design was not pursued due to time and complexity constraints. Requirements for a fully operational fleet-ready system are more stringent, require greater tests, and meet higher levels of safety and qualification than a prototype system. When designing a prototype, issues such as long-term storage survivability and interface with projectile handling equipment are secondary and do not drive the design. Prototype design involves identification and management of risk and focuses on testing to gather data to mitigate risk. This is useful when designing a first-of-a-kind system where pure analysis is not guaranteed to cover all possible scenarios. However the design of the HGV was intended to model the Operational Vehicle as closely as possible, and serve as a base configuration for finalizing the design into a qualified, fleet-ready product. Certain aspects of the design would require more detailed evaluation to meet operational requirements, but the development and design of the HGV solves many of the more stringent functionality issues.

3.2 Flight Test Vehicle Design

3.2.1 Overview

Since the most important aspect of the Flight Test Vehicle was the electronics and the flight operation, the most important consideration was to fit the necessary components into the smallest volume possible, since the optimum scaling would be the closest size to the HGV. Volumes of the each component listed on the Component List for the FTV (Appendix B) helped to judge the initial scaling, and more detailed dimensions in each axis were also listed to accurately model the shapes. Propulsion components, wings, tails, and the power system were also scaled up and modeled after the HGV design.

3.2.2 FTV Structure

Externally, the shape of the FTV replicates the HGV. For weight and ease of construction, the materials are different and the internal structure is designed around the electronics. The nose cone surrounding the engine is made of curled aluminum sheet metal with cutouts for the engine components. A wood and plexiglass engine mount connects the engine module to the main body. The body consists of a long aluminum tube with internal mounts for the electronics shelf and external mounts for the wing halves. The rear of the main body is closed by a stereolithography-type resin structure that supports the tails, tail actuators, gears, recovery chute servo, and camera. The optimum layout that allowed the least amount of scaling was found by modeling the dimensions of each electrical component on the CAD program Pro Engineer. A drawing of this configuration is shown in Figure 3.3 with the main components highlighted.

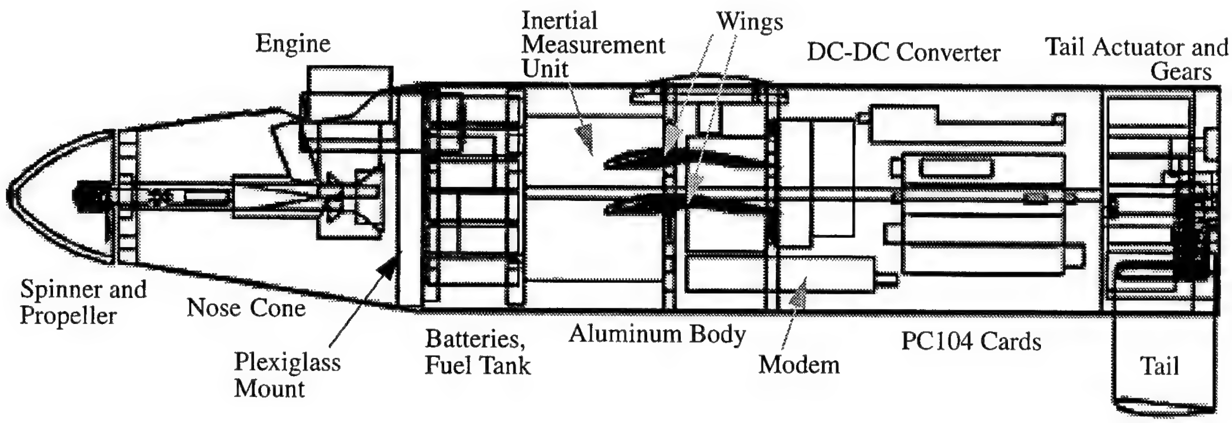


Figure 3.3: Side View of FTV Layout

3.2.3 Propulsion

The FTV uses a larger version of the same engine as the HGV. It produces 300 Watts of power resulting in 1.46 pounds of thrust. Manufactured by OS Engines, Japan, these engines and all related components such as mounts, fuel, and starting mechanisms are available at most hobby shops carrying model aircraft supplies. The propeller is similar to the custom propeller made for the HGV, but is limited to commercially available sizes. Starting of the engine is done using either an electric spin starter or by spinning the propeller by hand with a rubber tube. Engine-produced vibration can affect the operation of the electronic components, therefore the mounts for the engine and for the components had to be designed to absorb and reduce the vibrations.

3.2.4 Electronics

Electronics for the Flight Test Vehicle were chosen as the requirements and necessary components for flight control were determined. These electronics provide autonomous control of flight along a predetermined path, sense and counteract flight disturbances, and stability augmentation. A receiver and transmitter system on-board is able to receive remote operator commands that override the autonomous flight and transmit telemetry data. The link diagram is shown below in Figure 3.4, and shows the remote control that can be input when necessary. The detailed design and integration of the FTV communications and electronics and the ground station are discussed in References [18] and [19].

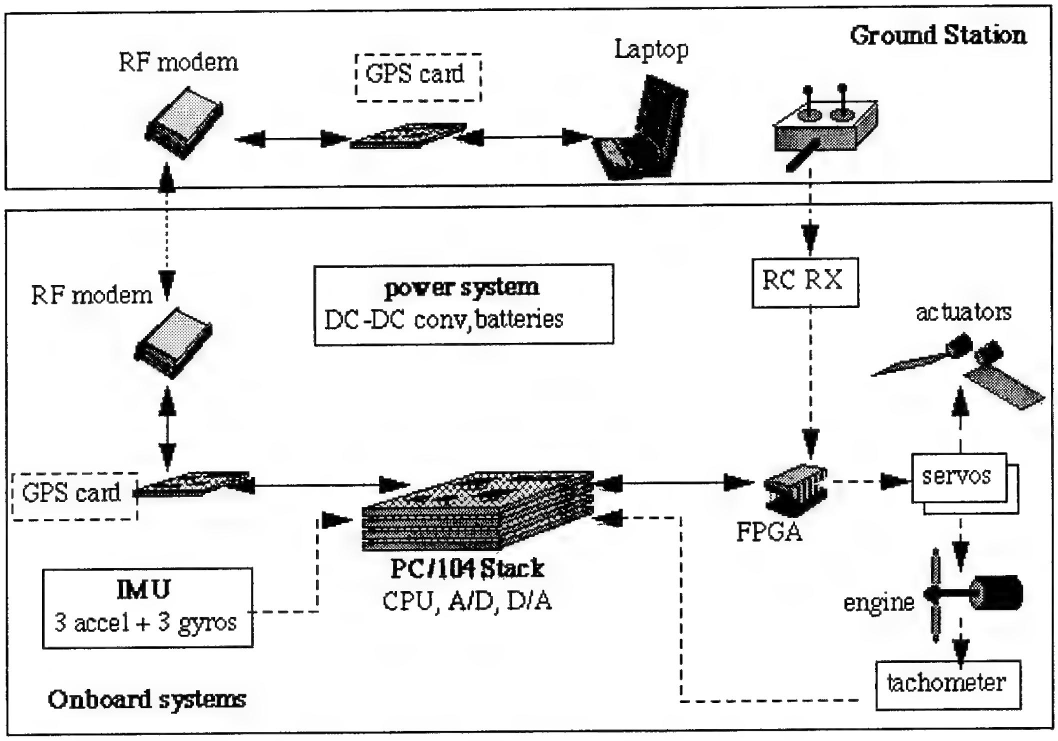


Figure 3.4: Link Diagram for Flight Test Vehicle

Prior to actual flight, the electronics and the flight of the vehicle were simulated in the laboratory. Using a simulation program developed by Draper Laboratories, the FTV team was able to link the electronics used on the flyer to a virtual flyer on a computer simulation. The digital flyer incorporated performance characteristics of the real vehicle, allowing a controller to practice the actual flight. Aerodynamic data for the vehicle was recorded in MIT's five by seven foot wind tunnel. A schematic of the simulation and links is shown in Figure 3.5 below. This setup allowed the human controllers to view the vehicle's control response on the simulation prior to vehicle flight. The simulation was expanded to model portions of the operational vehicle's mission, such as gun launch, ballistic flight, and the deployment sequence. Known aerodynamic data for the vehicle's launch support system was used where possible. This simulation is a valuable asset to train operators, demonstrate the mission profile, and experiment with altering aerodynamic values or sequences of events.

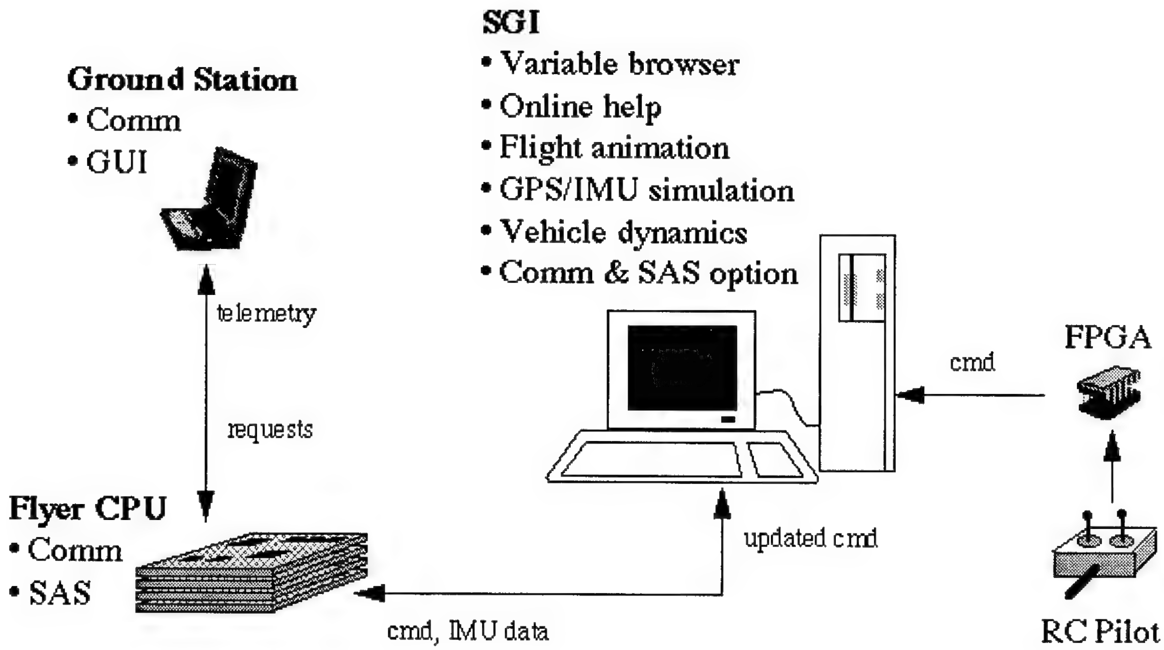


Figure 3.5: Schematic of FTV Flight Simulation

3.2.5 Power System

The power requirements are determined by the power draw and efficiency of the electronic components within the FTV, shown schematically on Figure 3.4 above. These requirements are shown in Table 3.1. FTV Power is provided by a rechargeable battery pack. A detailed design and discussion of both the FTV and operational vehicle power systems can be found in Reference [20].

Table 3.1:Flight Test Vehicle Power Requirements

Component	I (Amps)	U (Volts)	P (Watts)
GPS Receiver	0.28	5	1.4
GPS Antenna	0.05	15	0.75
IMU	0.23	+- 15	3.50
IMU Filters	0.01	+- 15	0.15
CPU	0.98	5	4.90
Ethernet	0.4	5	2.00
Serial Ports	0.4	5	2.00
A/D Converter	0.01	5	0.05
	0.01	+- 12	0.12
Modem	0.2	5	1.00
Servos	0.3	5	1.50

Table 3.1:Flight Test Vehicle Power Requirements

Component	I (Amps)	U (Volts)	P (Watts)
RC Receiver	0.014	4.8	0.07
Engine (glow plug)	1.25	1.5	1.88

3.3 High-G Test Vehicle Design

3.3.1 Overview

The HGV is designed to test the mechanical and structural integrity of the vehicle design. It is the prototype operational design, containing the necessary space for current Draper electronics needed in the final system. More space will become available given the current trend towards more compact electronics. After verification of the vehicle's design, the team had planned to test as many other system interfaces and systems as possible, including flyer deployment, incorporation of electronics and necessary electrical connections, deployment of aerodynamic surfaces, and operation of the engine. Testing of each of these aspects was not realized for reasons covered in Section 6.4, but much of the internal flyer design and functionality was verified. The design of the HGV is covered in detail in the following sections.

3.3.2 Flyer Design

The flyer concept is based on a modular design that is easy to machine and assemble. It consists of three structural modules; the forward propulsion module, mid-section wing module, and the aft section tail module, shown with all components fully deployed in Figure 3.6. The propulsion module contains the propulsion system for the flyer and is located at the nose. It is threaded to the wing module, which houses the propulsion fuel tank, battery, and the wings themselves. Sufficient space was available beneath the wing area for a camera to be incorporated as compact high-g instruments become more available, but was not included in the prototype design. The module farthest to the rear is the tail module, which contains the controllable tail surfaces, servos, and flyer guidance and control electronics. Each module is made of aluminum, a strong yet lightweight material that has proven its survivability in existing projectiles under extreme launch forces. Through analysis and testing, the modules were able to survive launch accelerations of 15,000 g's and more. The aft modules had to be thicker to support the weight of each for-

ward module. Modules were also designed to be machined quickly with conventional tools, helping to reduce the cost of the final design iteration. Modularity also allowed concurrent design and development processes within the different modules. Detailed discussion of the module designs and integration of the electronics is contained in Reference [21].

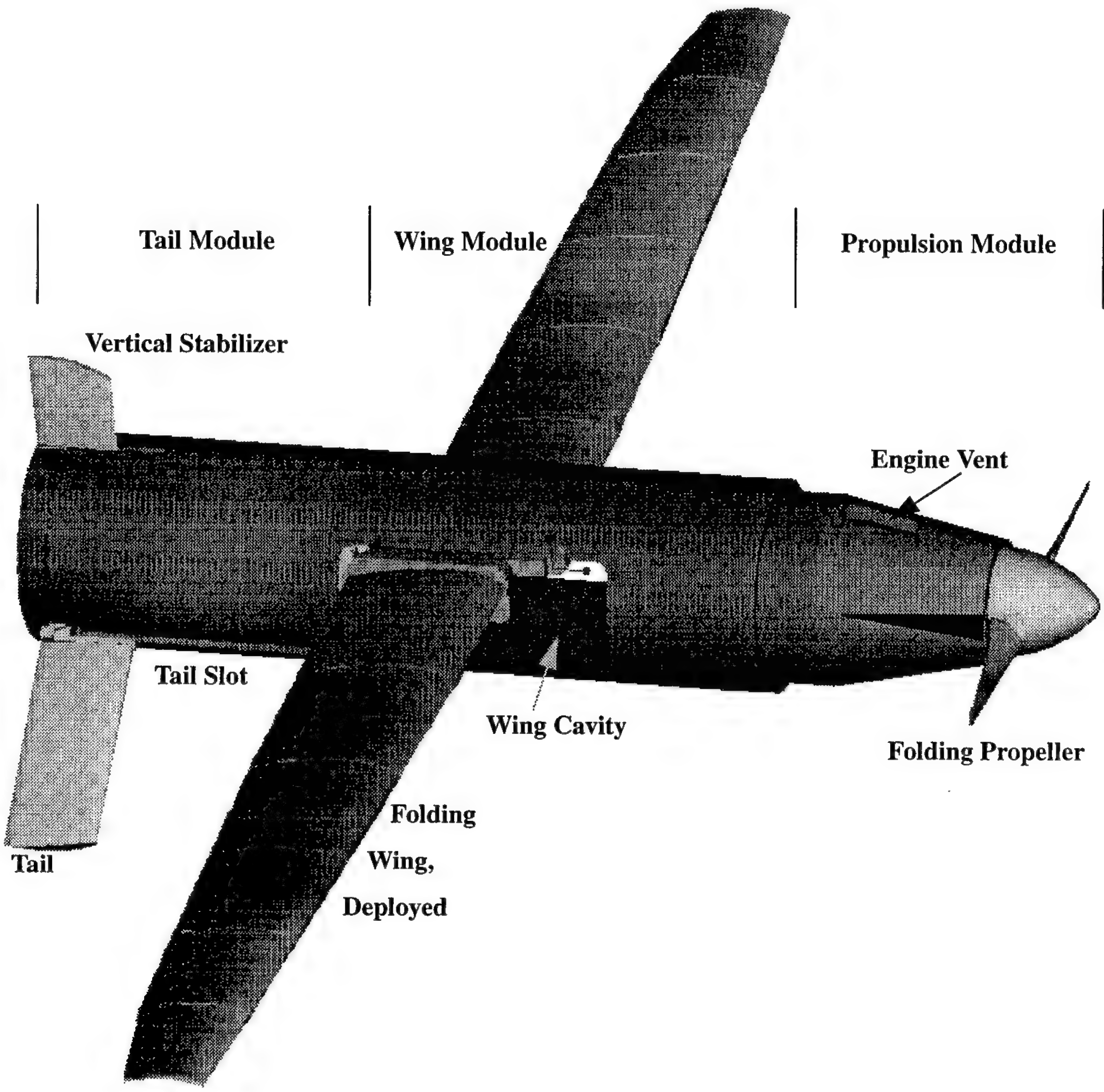


Figure 3.6: Fully Deployed High-G Flyer, With Modules and Features Labeled

3.3.3 Propulsion

The propulsion system consists of the engine, fuel tank, and throttle servo. Remote control aircraft internal combustion engines were chosen due to the compact weight, high power per volume, and proven functionality. Initially a Wankel engine was favored over a two-stroke engine, since it contains less moving parts. Testing demonstrated that the Wankel structure was susceptible to breakage at key locations, and the design progressed with the two-stroke engine. Electric engines were also considered but failed during testing. Parts did fail on the two stroke engine but this could be prevented by sound design of a supporting structure. Fuel for the engine is contained in a tank at the top of the wing module which is sealed by attachment of the propulsion module (see Figures 3.6 and 3.7). A small micro servo mounted within the propulsion module controls the throttle.

3.3.4 Wings

The wings are a unique solution to the design constraints of the vehicle. Due to the limited space available for the wing while the flyer is within the shell, the wing combined machining capabilities and wing geometry to produce an unprecedented concept. Initial concepts such as telescoping wings and inflatable wings were researched extensively by the team members. Telescoping wings would involve sliding and very close tolerances between wing sections which could lead to jamming and would need an active deployment mechanism. The projected stiffness of the wings was analyzed and resulted in large tip deflections. The span of the wing remained a function of the shell diameter, since each telescoping section was designed to fit within the flyer diameter. Research and analysis of the inflatable wings tended to be discouraging in terms of volume usage and performance. Work on alternative wing arrangements continued as the initial concepts continued to encounter problems.

The idea of using folding wings led to the current design. Initially the concept had many of the same problems with size limitations. Placement of the wing along the flyer center axis solved this problem by limiting the chord of the sections but not the length. Section length would be constrained by the length of the area allowed for the wings. Therefore the span length became flexible, and could be adjusted depending on the amount of lift required. To deploy, the wings rotate around a pivot joint at the rear of the first section. Folding wing sections and aerodynamic

performance required each section to have a significant camber, allowing sections to fold within one another. The complete design and development of the wing to survive the launch forces is covered in Reference [33]. A view of the folded wing rotated outward from the wing module is shown in Figure 3.7. The wing cavity cover and forward acceleration support shown were added in the final stages of the design.

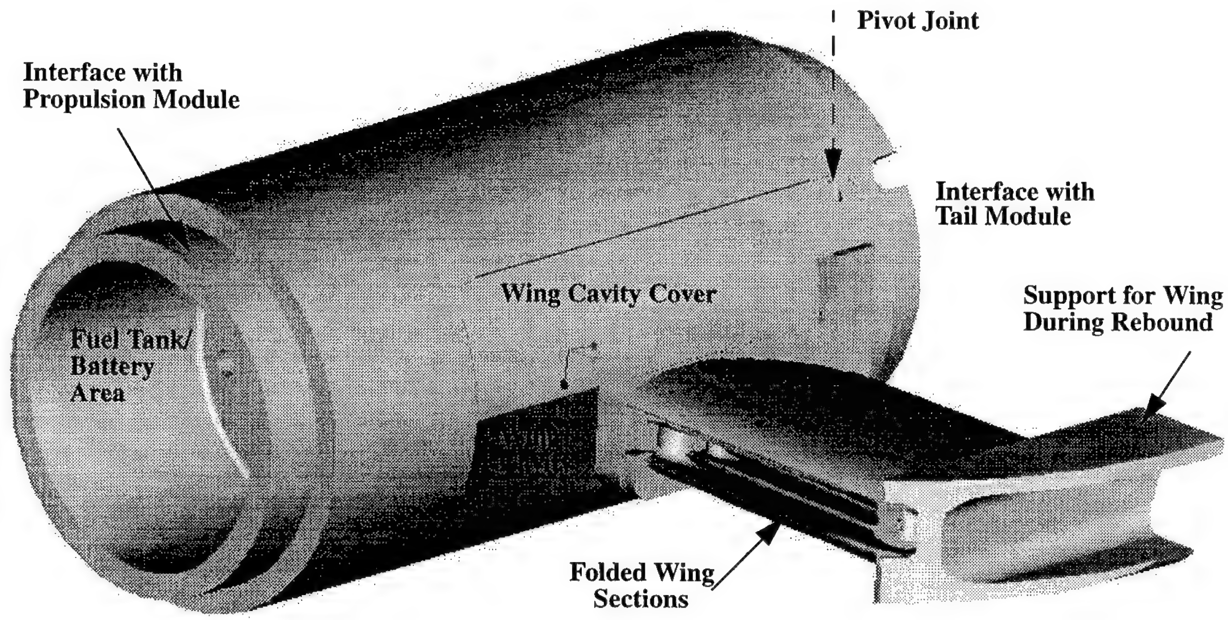


Figure 3.7: Folded Wing and Wing Module

3.3.5 Flight Support and Deployment System

The flight support and deployment system for the vehicle consists of the modified illumination round shell, a nose cone, the clamp attachments, and a modified shell base that supports the stabilizing tail fins and parachute system. A three dimensional model of these components including the stowed assembly of the flyer (but without the nose cone) is shown in Figure 3.8 below. The primary purpose of the flight support and deployment system is to interface with the gun environment, support the flyer, and implement the deployment sequence. Since the operations are performed during the unguided portion of the flight, the overall system is referred to as the ballistic system. This system is massive compared to the flyer itself, which reduces the acceleration forces experienced at launch and results in longer ballistic range, as mentioned under the design guidelines of Section 2.2.1. The system design allows the flyer to be as light as possible

for its mission. Evolution of the concepts, detailed design, analysis and testing are covered in the Sections 4.0 and 5.0.

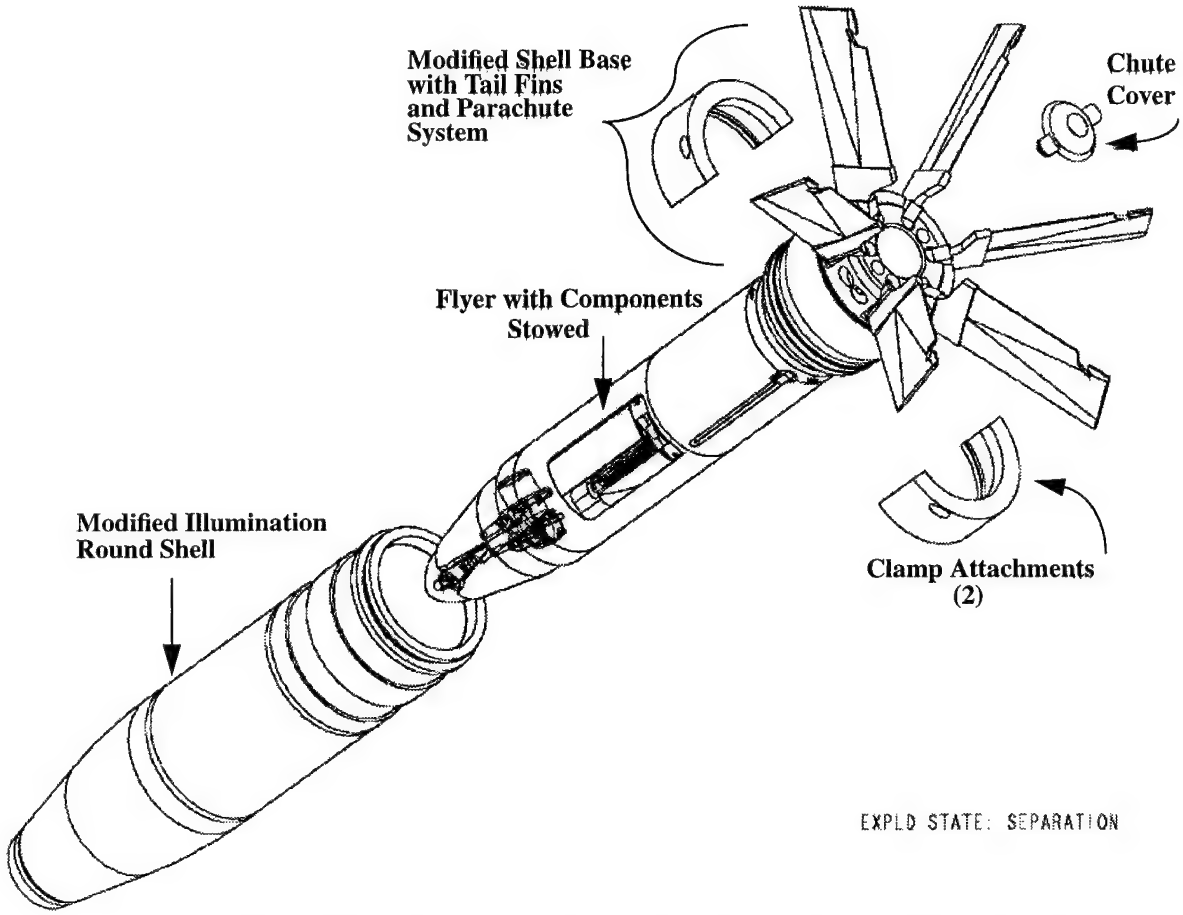


Figure 3.8: Model of Flight Support and Deployment System with Flyer Assembled

4.0 Flight Support System Design

Flight support refers to the components of the vehicle that perform their primary functions during the launch and ballistic flight phase. These components include the projectile body, its base, and the nose cone. For the illumination round, the flight support system consisted of the projectile body with obturator bands on the external surface, a circular plug for the base, and a nose fuse containing the deployment explosive. Detailed engineering drawings for the projectile body and base plug of the illumination round are contained in Appendix D. Information on the complete illumination round assembly within the projectile was also received from NSWC Crane.

Projectile bodies for the illumination round are cast from 1050 steel with a controlled percentage of manganese. Base plugs are press fit into the rear of the body, and a nose fuse is threaded into the nose cavity. The base plugs seal the illumination round within the projectile, support the system during launch pressures and accelerations, and assist the deployment of the deceleration parachute when ejected. WASP required the base to support more components and contain greater functionality. A new base design was necessary to incorporate the gun interface, stabilizing tail fins, deployment mechanisms, and parachute systems.

4.1 Guidelines

As the specific functions of the flight support system became apparent, the design process incorporated external interfaces with standard five inch guns and internal interfaces with the flyer, parachute system, and tail fins. As designs of the other components progressed, the concept was altered to accommodate the requirements of the mission.

4.1.1 Gun Interface

The base is the rear most structural support component of the vehicle structure when configured for launch. It is exposed directly to the pressures and combustion flames from the launch propellant. Pressures act on every surface aft of the obturator band and accelerate the entire assembly to ballistic flight speeds approaching Mach 2. The base must be designed to withstand these pressures and support the weight of both the flyer within the projectile body and the body itself.

Initially it was assumed that the obturator positions would remain at the same locations as the illumination round, which uses two bands towards the aft end of the projectile body. The two obturator bands would be replaced with slip obturators. Since no slip obturators had been used on illumination rounds, this would have become another design hurdle requiring tests to ensure successful operation. During consultation with engineers and designers, it was learned that the tail fin assembly used an obturator at a different position for a projectile of similar dimensions. This information made it possible to incorporate an existing slip obturator into the base design.

4.1.2 Shell Interface

The dimensions of the illumination round projectile body (referred to as the shell) set the geometric limits for the dimensions of the flyer. With the detailed dimensions of the shell known, both the flyer and shell were modified to provide sufficient volume for the flyer and the necessary structural support.

The fleet-issue shell has material in the nose that reduces the volume available for the forward end of the flyer. Design of the flyer around this material would also have severely affected aerodynamic performance. Configuration of the flyer required more volume than was available. Modification of the internal area of the shell would increase the volume and improve the flyer's shape but could compromise structural integrity.

The base plug of the illumination round required only a tightly controlled, smooth inner step on the aft end to support the press fit. A base that incorporates more functions than the current base plug could require a more complicated method of attachment. The deployment method would also have to be altered to avoid locating the explosive in the nose. Explosive placement could also affect the interface between the base and the projectile body.

4.1.3 System Stability

The current illumination round is spin-stabilized during its ballistic flight until the RAID chute is deployed. Early in the development of the flyer concept, it was determined that spin stabilization would be very difficult due to the moment of inertia constraints that would determine how the interior components were arranged. Electronic components are also affected. For example, oscillating crystals in the GPS timer components exhibit sensitivity to spinning at high rates for longer than several seconds. The only alternative to spin stabilization is to use fins to stabilize the projectile. The fins cause pitching moments around the center of gravity that maintain projectile stability under side forces such as changes in air flow surface pressure. Fins effectively move the center of pressure to a point behind the center-of-gravity (c.g.). The aerodynamic properties of the fins must be sufficient to move this center of pressure behind the c.g., and by design of the flyer and base, the c.g. is as far forward as possible. Support for a fin stabilization system would have to be incorporated into the design of the back end or added to a modified shell.

4.1.4 Flyer Attachment

Due to the parallel walls of the body the flyer rests completely on the base. The base must support the accelerated weight of the entire flyer during launch and keep the entire system enclosed and firmly attached to the shell. Forward sections of the shell are also likely to absorb the force of the flyer within the shell during rebound. Upon deployment, the base and shell attachment must be released to extract the flyer. In the final operational sequence, the parachute system assists flyer extraction by providing a reverse force on the base and flyer assembly (see Figure 3.2), pulling the assembly out of the shell as the shell's momentum carries it forward and away. Following complete flyer extraction, the base/flyer assembly continues to decelerate together to a safe flight speed and wing deployment dynamic pressure.

During deceleration, the control surfaces deploy and the engine starts using passive spring mechanisms pre-loaded before assembly. Air flow over the control surfaces and thrust from the engine provide stability and control. At this point the base separates from the flyer and the parachute and base decelerate further as the flyer begins its mission. Attachments between the base and flyer must provide strength during launch, ballistic flight, and deployment but separate cleanly at the correct points in the deployment sequence. Large forces between the base and flyer must be supported adequately until a clean separation allows the flyer to perform its mission.

4.1.5 Parachute System Integration

As noted above, the base separation from the shell and flyer extraction are closely linked to the parachute system operation. The ballistic system must contain and support the operation of the parachute system. Base design includes a cavity within the structure to contain the parachute components.

4.2 Concept Development

The concepts developed for the flight support system attempted to use designs similar to existing systems. Design of the system is tightly linked to the method of separation and functionality the base is required to support. Guidelines were used to develop and refine the concepts as the design progressed.

4.2.1 Concept Generation

The concepts discussed here focus on the incorporation of the explosive separation mechanism between the base and the shell. A separate concern for how to integrate the fin system into the constrained area of the base is discussed in Section 5.1. Initial efforts were made to keep the overall system length the same as a standard Mark 64 or Mark 48 illumination round, since it was believed that this would improve the gun interface and auto-loading mechanism. The difficulty of integrating an effective fin stabilization and separation mechanism with enough material to support the vehicle became extremely difficult under this constraint, and many examples of current projectiles of varying length were found. As the size and complexity of the designed systems became apparent, the constraint on the length was relaxed. This allowed more volume for the flyer, freedom to extend the length of the vehicle if necessary, and improved the quality of concept generation.

The first alternative concept used the same base and shell attachment with the charge located at the rear of the shell instead of the nose. Placing a charge in the forward end of the shell was risky, since the combustion gases and pressure generated must travel over and around the components on the surface of the flyer, including the propeller, engine, wings, tails, and camera. Simply locating a similar size charge at the rear, for example around the circumference of the inside shell wall, would produce the necessary pressures and force to eject the back end successfully. This would still affect the flyer surfaces and place the charge near the folded parachute. Attachment by either of the current methods, threaded or interference, was possible.

To avoid applying direct pressure to the flyer and risking the parachute, a later iteration proposed to put the explosive charge within the base structure itself. Channels cut into the base would allow the gas pressure to impinge directly on the attachment between the shell and the base. This would partially protect the flyer from the pressures and combustion gases and still provide the necessary ejection force. The charge would also not have to be located between the base and flyer, a vital support area for the flyer structure.

Another option was to avoid exposed explosive charges to generate pressure and use a more controlled method of separation. Explosive bolts were proposed as the attachment mechanism. The bolts would secure the base to the shell during launch and ballistic flight. When activated, explosives within the bolt would fire, causing the bolt to shear and release the force holding

the shell to the base. An ejection force would still be necessary to reliably separate the base and flyer and assist in parachute deployment.

Many other concepts were also considered. Due to the uncertainty encountered with press fits, and difficulty of disassembly, a pinned attachment system was also examined. Pins inserted between the base and the shell would support the base under axial forces. They could be designed to shear at a specific pressure or force. Mechanical designs that would eject or retract the pins were examined in detail with analysis determining the number of pins necessary to hold the base and the geometrical constraints.

Initial configurations placed the parachute system within the shell, between the base and the flyer. The parachute components were contained in a "cup" formed by the back end structure. This arrangement reduced flyer support and led to difficulties integrating the attachment and separation mechanisms. In the deployment sequence for this configuration, the base and fins were separated first and assisted in the chute deployment (Figure 4.1). Analysis demonstrated that after base separation the lack of tail fins would cause the parachute, flyer, and shell to respond to flow instability and tumble within two tenths of a second. This time was too short to assume full parachute inflation and stabilization. A proposal to change the configuration by placing the parachute within the aft end of the base, and deploying it behind the base instead of the flyer, was suggested to solve the stability problem [23].

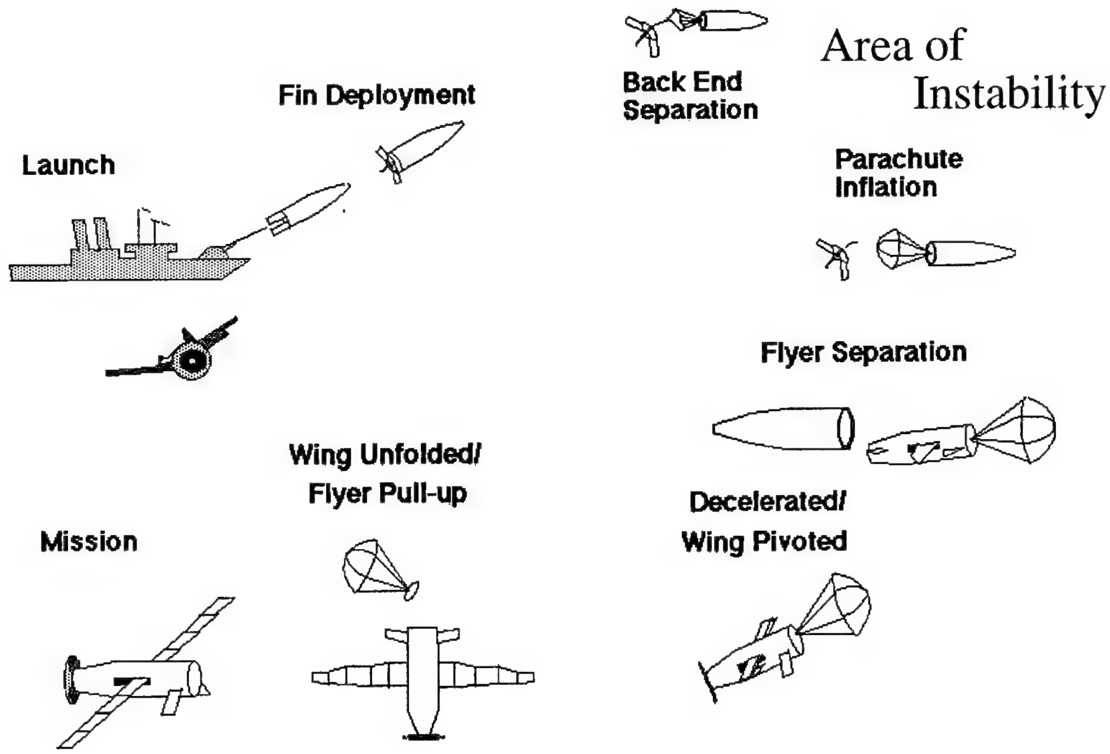


Figure 4.1: Initial Operational Sequence Showing Area of Possible Instability

The base would support the parachute system within its structure, and a separate cover would be necessary to protect the parachute during launch. Deployment of the parachute behind the base would extract and decelerate the base and flyer assembly together. With this arrangement the fins provide system stability until the flyer is decelerated and able to stabilize itself. Benefits of this configuration soon became obvious. The fins maintain system stability during the dynamic events of parachute deployment and flyer extraction. Removing the need for a parachute cavity between the base and flyer frees more volume and provides better structural support for the flyer. A smaller parachute cover forcefully ejected could provide the parachute deployment assistance previously provided by the base. And the parachute would not be close to any separation explosives.

Upon consultation with faculty [24] it became obvious that what the team considered a unique separation problem was similar to problems encountered in designs of payload delivery vehicles: the challenge of attaching a payload and vehicle together to resist forces encountered during flight and then deploying the payload successfully when commanded. Previous concepts beyond those for illumination rounds were researched, encompassing satellites, aircraft, and mis-

siles. One common mechanism for attaching satellites to launch vehicles is the Marmon clamp, which is a band of material around the circumference of a circular payload/ vehicle connection. The material supports a strong, tight band pressure around the entire circumference but can be broken at one point. This point is designed to be sheared or failed with a highly concentrated explosive, which releases the entire attachment force. This allows the clamp to provide a large area of clamping force that can be released with a relatively small activation requiring little power. Use of circumferential attachment on the shell would be possible if the diameter at all points is less than five inches. A concept based on the Marmon Clamp idea was developed that used grooves within the base and shell to clamp the two components together.

4.2.2 Concept Evaluation

The risk of damaging the stowed flyer drove concept evaluation. Initial concepts used fuse-activated explosives placed within the shell to separate the back end. Activation of the fuse ignites the explosive, and the pressures build over a finite amount of time. It had been learned in tests conducted by the Navy that fast explosives did not generate the necessary sustained pressure to separate either the press fit or threaded attachment. The explosive used had to generate a pressure between eight and fourteen thousand pounds per square inch depending on the speed of pressure build-up [14]. These pressures could damage parts of the operational flyer such as the engine or the camera lenses. Designs containing an explosive that could affect the flyer were risky to the success of the entire mission. Research into explosives and alternative separation methods focused on finding a way to avoid affecting the flyer.

Research into commercially available explosives assisted in determining the separation concept most likely to succeed. While investigating the base separation schemes, contacts were made with companies specializing in explosive devices who sent information and data on the types of devices available. Information applicable to the WASP is contained in Appendix E. This information was used to choose an existing explosive bolt design to connect the flyer and base. By using an explosive bolt currently in production the bolts were acquired at low cost and set up a good contact with the manufacturer, Special Devices, Incorporated (SDI) [25].

The first concept had the explosive in the back end with a barrier placed between the explosive and the flyer to protect the flyer components. However, an effective barrier proved difficult to integrate into the available volume and could not be proven to protect the flyer. The generation of pressure requires a volume within which it must be constrained, with only the option of breaking the back end attachment to be released. Therefore any barrier would need to resist the pressure more effectively than the back end attachment, and be removed or avoided when the flyer is extracted. This would require more volume than was available and further alterations to the shell.

Putting the explosive in the back end structure encountered the same problem. Although the explosive itself would be housed in the base, the gases and pressure generated would expand into the shell and act on the flyer. Therefore the design was considered to be as problematic as the first, and was not pursued in detail.

The use of explosive bolts was researched extensively for the base and shell attachment as well due to their ability to handle high loads and release when fired. The geometry of the shell and the available material, however, made this a weak approach. Assuming the weight of the flyer was resting entirely on the base, as it would be for a completely inertial acceleration, the force the base must withstand would be given by simple physics (F=ma). With an estimated flyer weight of 23 pounds, and an acceleration of 12000 g's, this results in 254,000 pound-force. Assuming the maximum possible tensile strength bolt, with 10 threads per inch and diameter 0.375 inches, the base would need 15 axial bolts to contain the base to the shell. Analysis for a flat base demonstrated that significant shear forces would also act on the bolts. Addition of a lip of material extending from the base into the shell would use the shell circumference to support shear forces on the base. The lip would reduce the available volume and move the flyer interface location farther to the front of the shell, limiting the length of the flyer body.

In this arrangement the bolt heads would be outside the shell and facing the aft end. Bolt assembly would require material removal from the base sides to fit tools that could tighten the bolts effectively, or the bolts would have to be long enough to be inserted from the very aft end of the base. Explosive bolt activation wires enter the bolt through the head, making electrical connection difficult after assembly of the vehicle. A connection would have to be made at some point on the outside of the shell and be subject to the gun environment. A possible configuration that would encounter many of these same problems is shown below in Figure 4.2.

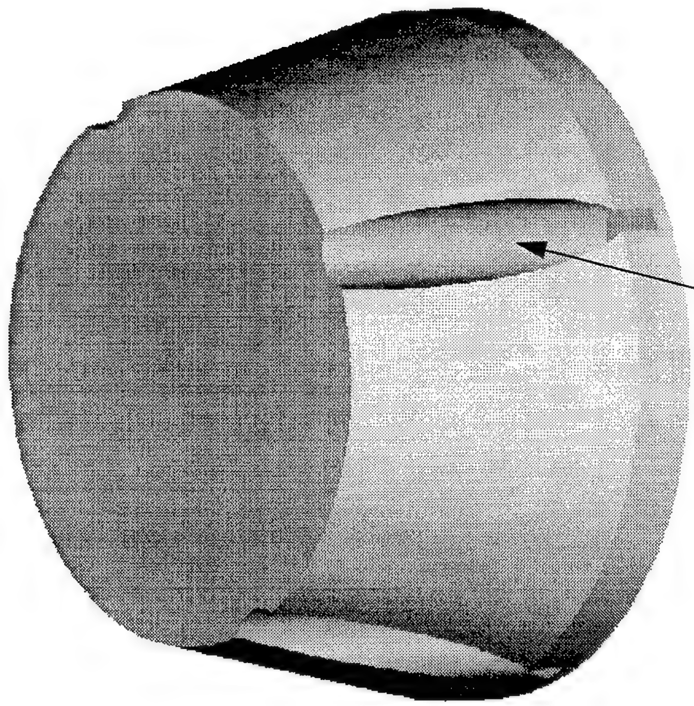


Figure 4.2: Geometry of Base for Explosive Bolt Attachment

Loading either explosive bolts or pins in shear, not tension, would allow the bolts or pins to be inserted radially. Shear areas for bolts is given by:

$$A_{ts} = \pi n L_e K_{n_{max}} \left[\frac{1}{2n} + 57735 (E_{S_{min}} - K_{n_{max}}) \right]$$

A shear area of 24.38 inches squared would require six 0.75 inch diameter bolts, which was difficult to incorporate into the structure. It was considered risky that pieces of the pin or explosive bolt, if inserted radially, could interfere with extraction of the flyer. As with either longitudinal or radial arrangement, a separate ejection force would have to be applied to the base itself to clear it from the shell and assist with parachute deployment. Despite these problems, this method was initially seen as the most likely to work and easiest to incorporate.

After development of the clamp arrangement, many of the problems with the other concepts were solved. The clamp arrangement allowed the load path to be maintained through the base into the shell for the forward acceleration. During rebound, the clamp material within the grooves of the shell and base would support the tensile forces. Although the material does not

allow for large bolts, the load path does not pass directly through the bolts themselves. This design addressed many of the problems that surfaced during development of the initial concepts. This led to concepts using ideas similar to the Marmon clamp attachment mechanism.

4.2.3 Concept Selection

As concept generation and evaluation progressed the concepts were reviewed by faculty and team members. The research into each separation scheme and the problems associated with many of the first iterations led to the selection of the clamped system. This system solved the problem of interfering with the flyer, allowed a more complete structural load path for acceleration and rebound, was easier to assemble and disassemble, and involved a simple geometry. Any explosive separation mechanism would be isolated from both the flyer and the parachute. Detailed clamp system design is reviewed in Section 5.3.

4.3 Detailed Design

4.3.1 Overview

Flight support system design was updated repeatedly to accommodate support of the various components and structures necessary to the system. Part machining is possible on the machine tools of well-equipped machine shops. An assembly showing the design of the flight support system is shown in Figure 4.3 below. Engineering drawings of the shell, base, and the support structures for the fins and obturator are included in Appendix F.

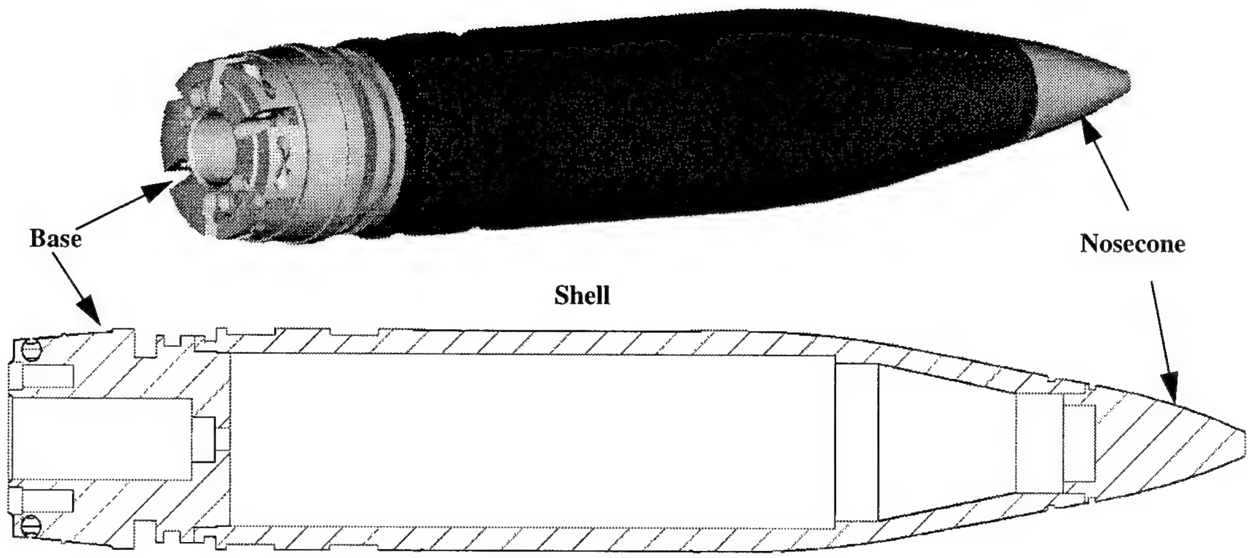


Figure 4.3: Assembly and Cross Section of the Flight Support System Components

4.3.2 Nosecone

Design of the nosecone for the vehicle is simple since it exists solely for interface with the gun handling processes and aerodynamic flight of the ballistic system. Currently the nosecone is made of hardened 1050 steel and follows the contours of a standard cargo round fuse. Material could be removed or added to the nosecone to assist placement of the center of gravity with respect to the center of pressure. If testing showed that flyer deployment was unreliable, a mechanism to assist the flyer exiting the shell could be placed within the volume of the nosecone. An interface that connected the gun mount control to the flyer, that would be active with the flyer inserted, could also be designed into the system if this proved valuable.

4.3.3 Shell Modifications

Calculations performed while evaluating the vehicle concepts demonstrated that buckling, the most likely mode of failure for a thin walled projectile, would not be likely to occur at the current launch accelerations [28] after removal of a significant amount of material. Removal of material at the nose of the current illumination round should not jeopardize the structural integrity of the projectile body. The illumination round body had two steps in the cross-section contour

that formed concentric cylinders within the shell nose. These steps were removed by cutting a cone shape roughly following the outside contour up to the fuse cavity. The team attempted to maintain a minimum material thickness of a half inch in the nose while removing material for the flyer propulsion module. The material removal allowed the module shape to be a smooth cone, resulting in a more aerodynamic profile for the flyer. A step in the shell was left to provide structural support during rebound. Analysis of the propulsion module demonstrated that it could support the rebound force of the flyer along only the step, in case the sloped area did not provide structural support [21]. The step also prevented jamming of the sloped propulsion module into the shell nose.

The clamp attachment provided a simple way to securely attach the base and shell. The shell required modification to its aft end for attachment of the clamps. In order to support the weight of the flyer and shell on the base, the shell rear was flattened where it interfaced with the base by removing the lip of material that extended beyond the step at the rear of the body. For the clamp, lack of material was a major constraint. A design was developed around the clamp concept (discussed in Section 5.3) that required only a groove in the outside of the shell. Material had to be cut from the outer diameter, to provide a groove for the clamp and then a space for the clamp thickness to pass around the outer diameter. The length of material removed was limited by the position of the current obturators since at these locations the body thickness is reduced. Figure 4.4 is a detailed view of the modifications as seen in the body cross section.

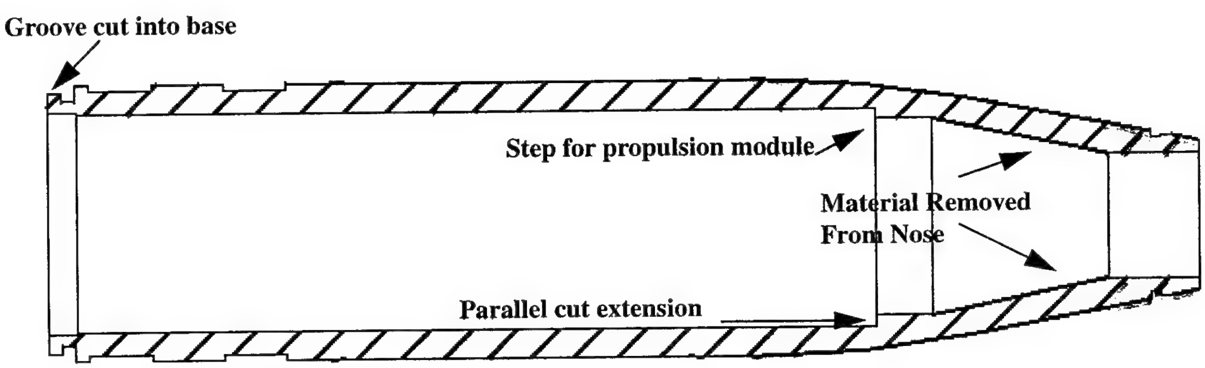


Figure 4.4: Cross Section of Projectile Body With Modifications

4.3.4 Base Design

Towards the later stages of the base design it was learned that the obturator position could be incorporated into the base structure with less risk than altering the current illumination round obturator. Existing slip obturators for a different five inch projectile were provided by the engineers at the Dahlgren Test Facility. Figure 4.5 shows the sloped cutout around the exterior of the base that supports the obturator. It is adapted straight from the engineering drawings of the projectile assembly currently using the identical design. The obturator is a solid nylon band designed to have a tight fit with the support structure. A tight clearance ensures that the obturator completely seals the gun breach while pressure builds and prevents blow-by of the launch gases. Special assembly issues are discussed in Section 6.3. The recessed groove prevents the movement of the obturator during the launch process. As the pressures of the gun barrel build, the obturator is pushed up the sloped groove to form an even tighter fit with the gun barrel. Sloping the groove allows for a more effective seal to form between the barrel and the projectile.

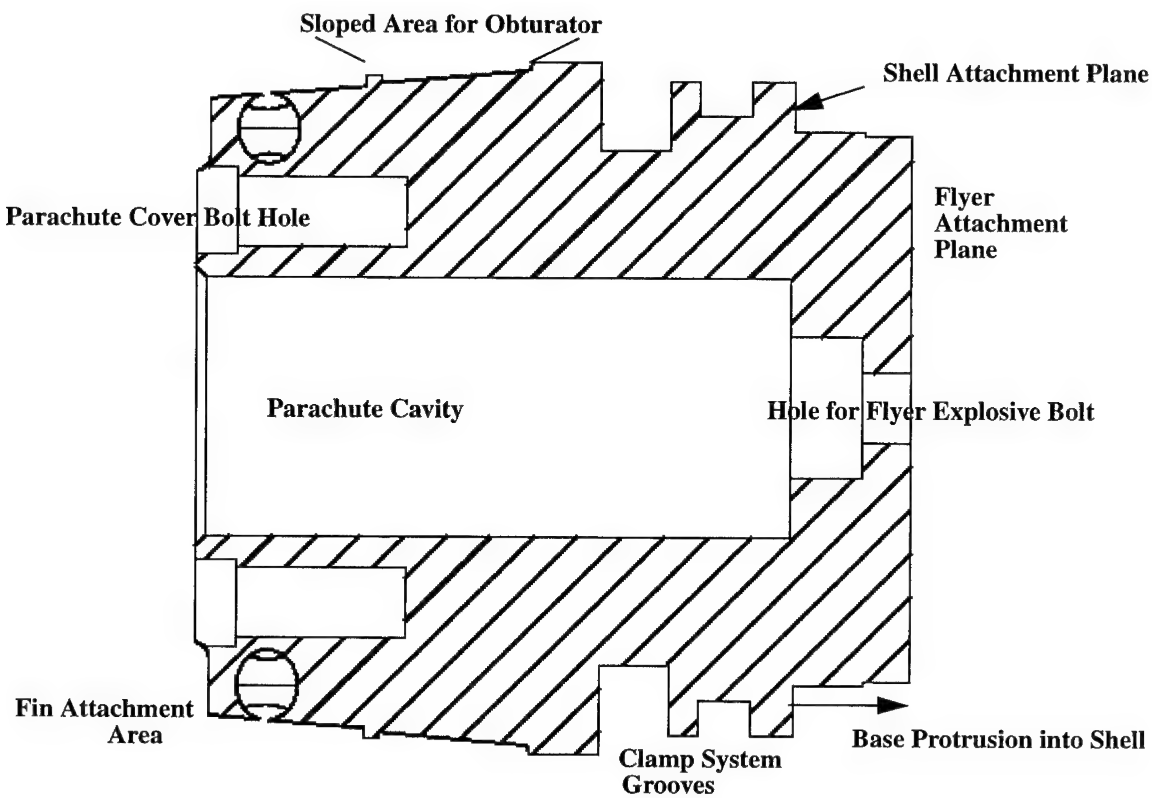


Figure 4.5: Cross Section View of Base Design with Major Features

With the flexibility to extend the shell's length a few inches, the design of the base left ample volume and material to incorporate the chosen fin configuration. The fin design required six fin axes to pass through the circumference of the base and half inch slots extended from the outer diameter inward 1.5 inches, and 1.25 inches deep to support each fin. Various other holes are incorporated in and around the fin support structure to reduce weight and support the fin system components. These features were all incorporated into the area behind the large groove in the base. The fin area can be clearly seen on the following view of the base (Figure 4.6).

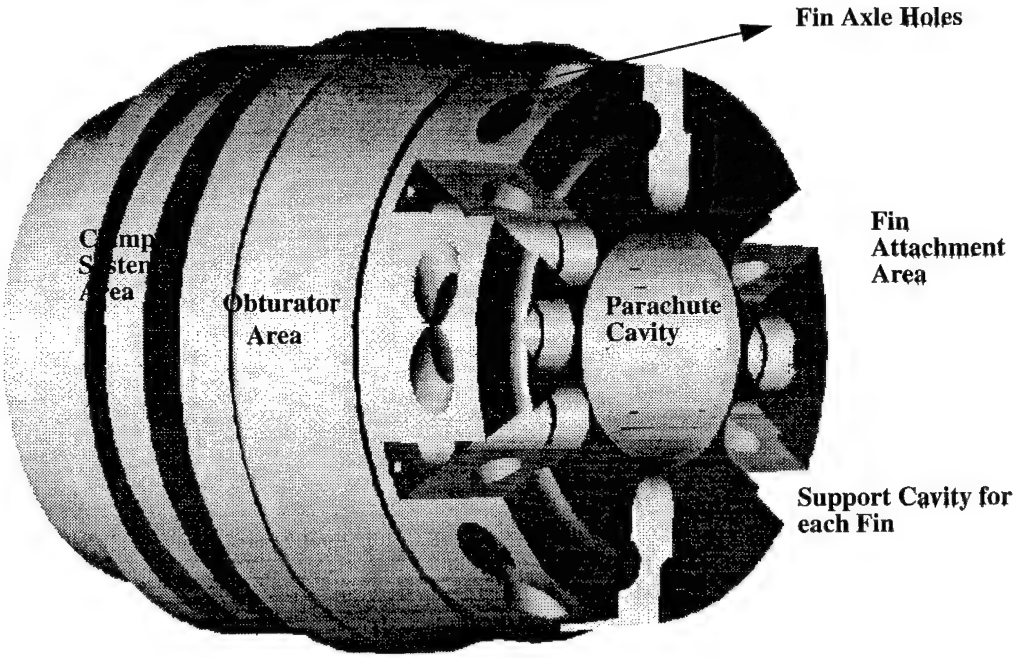


Figure 4.6: Model View of Fin Attachment Area

The original structure of the fin hinge plate has a cut-out cylinder beneath the fins. The cavity was a benefit to the vehicle design since it allowed easy integration of a parachute cavity. Fin deployment left ample space in which to deploy and inflate a parachute behind the projectile. The parachute cavity allows access to the flyer attachment and parachute plate which attaches the parachute to the base and flyer assembly. Folded and inserted over the plate is the parachute which is covered by the chute cavity cover. A ten cubic inch cavity was needed to fit the folded parachute. Due to the limitations of the fin attachments at the rear, the maximum diameter was 1.84 inches. This design limit forced the parachute cavity to measure 4.26 inches in length and became the biggest factor in lengthening the base beyond standard shell length.

The flyer attaches to the base with an explosive bolt that protrudes from the tail module and into the parachute cavity. A nut is screwed down over the explosive bolt and tightened prior to parachute insertion. This bolt will support the inflation and deceleration force between the flyer and the base/parachute assembly. This half inch steel explosive bolt is manufactured by Special Devices, Incorporated (SDI). Due to schedule limitations for development, the team chose to use a bolt that SDI was currently manufacturing. After assembly the nut is designed to lie flat with the remaining diameter of the cavity. These details can be seen in the cross-section view of the base in Figure 4.5.

A parachute plate attaches to the forward end of the cavity with two screws into the remaining diameter material. These screws secure the parachute plate to the base and transmit deployment, inflation, extraction, and deceleration loads. A swivel connects the parachute to the parachute plate and allows rotation of the parachute independent of the base and flyer system. The remainder of the cavity contains the volume of the folded parachute and is sealed by the parachute cover. Detailed design of the parachute cover is discussed in Section 5.4.

Complete integration of the base components developed by outside manufacturers would be likely to necessitate small changes such as channels for electrical connections and threaded holes not shown in the drawings. None of these changes would affect the overall design and arrangement of the base.

4.4 Flight Support System Assembly and Evaluation

4.4.1 Manufacturing

Manufacture of the complete base is complicated due to the fact that it contains different components, each with specific tolerances. The fins support structure requires lathe and mill operations with tight tolerances (attached in Appendix F). A complete base was not needed for testing therefore only an estimate for the manufacturing time can be made. A majority of the operations other than the fin support can be completed on a lathe. The most difficult parts were the holes for the fin axis supports. The fins rotate on the axle bolts placed through theses holes to deploy. These holes would have to be drilled from the side at a shallow angle to the curved edge of the base, crisscross one another repeatedly, and involve exact dimensions and lengths to fit the

bolts for the fins. Two simplified test articles were made, neither of which contained the fin support structure. MIT's Central Machine Shop and the machine shop at Draper Laboratories provided the experience, manpower, and tools and produced excellent test articles.

The shell modifications also involved lathe operations, but due to shell length it was sent to an outside contractor [26] for machining. The shop had no trouble modifying the shell to the specified dimensions. The most complex shell operation involved cutting the interior of the shell nose to increase the available volume. To reach the material a tool would have to fit through the small opening in the nose or reach longer than a foot through the larger opening at the rear. The parallel cut extension, as shown above in Figure 4.4, must maintain a straight parallel wall so that the flyer can be easily extracted. The steps of material at the nose had to be reduced to a slope that would match the propulsion module conic section. Slope angle was difficult to measure due to the blind cutting, and was specified as a reference dimension. If the assembly required changes, it would be a much simpler process to modify the propulsion module. The length from the flat end of the shell to the machined interior step had close tolerances to match the flyer length. The rear modifications to the shell involved simple lathe operations to remove material from the step and outside diameter. Minor modifications were still necessary during assembly to fit the length of the flyer within the shell and have the base sit flush to the shell. The initial cut left a small lip of material around the outside base, but this was able to be corrected in the Mechanical Engineering machine shop in 35-001 [27].

4.4.2 Time

The time required for each part could be reduced if the parts were produced in larger quantities. Table 4.1 shows the machining and setup time required for each part as well as the estimated time that would be spent in mass production.

Table 4.1: Machining Hours for Flight Support System Components

Component	Hours for First Design	Projected Hours for Production Run
Nosecone	8	2
Projectile Body	12	4
Support Base	28	12
Total	**48**	**18**

4.4.3 Finite Element Analysis

Analysis of the concepts and determination of the necessary geometry was done with the assistance of the COSMOS Fast Finite Element Solver and the CAD design software Pro Engineer. The Pro Engineer models were useful in visualizing design changes and were easy to update, allowing for quick and efficient evaluation of various designs. The analysis was performed with safety margins 25- 50% above the actual g-level, and boundary conditions were varied due to the lack of exact characterization of the environment.

Greg Kirkos of Draper Laboratories [28] analyzed the initial models of the Mark 64 projectile. His experience with the structural analysis of the ATD program allowed the WASP team members to benefit from verified analysis processes and the boundary conditions used in this loading environment. The boundary conditions consisted of an acceleration of 15,000 g's, pressure on the back end, a weight in the interior modeling the flyer, and varying shear forces from flyer weight. Explosive bolt concept analysis demonstrated the need for material within the shell to handle shear forces on the base. Simple shear calculations were also used to quickly analyze the bolt and pin concepts. The clamp concept was analyzed extensively and involved mostly the clamps and shell grooves. Clamp analysis results are discussed in Section 5.3.3.

To model the forces on the shell groove, a model of the shell from just forward of the groove to the rear face was made. A pressure equal to the weight of the entire shell body accelerated at 15,000 g's was applied to the cut plane where the shell weight is acting. A pressure representing the forward acceleration on the base plane by the base was applied to the bottom plane. The groove showed signs of failing with no material within the groove. A deformation limit representing the clearance of the clamp material within the groove was applied to the shell to simulate the presence of the clamp, and rounds were added at the corners to avoid singularities and stress concentrations. Results of the stress analysis for these conditions are shown below in Figure 4.7.

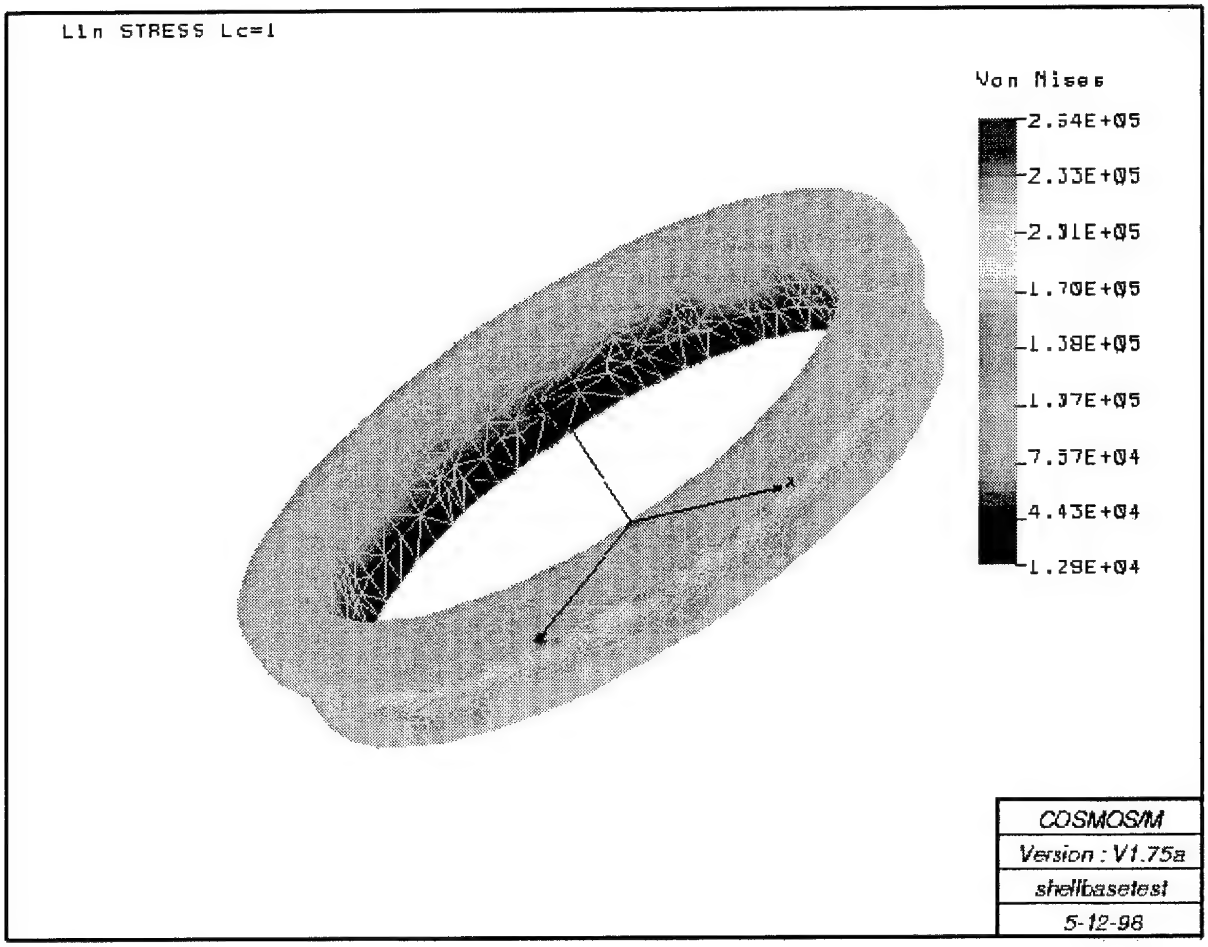


Figure 4.7: Finite Element Analysis of Shell Modifications

4.4.4 Flight Support Component Testing

The components that make up the flight support system should perform as designed due to the use of the shell and fins in existing systems. The various systems the base supports involve separate tests discussed later, but based on the design of the fin hinge plate and the obturator placement the base structure should be able to support the fin deployment and gun interface. Testing should focus on the survival of the clamp attachment system under launch loads. Section 6.0 reviews the results of the system testing.

5.0 Design of Deployed Systems

Deployed systems refers to the vehicle components that react to a command or force to deploy or are essential to the vehicle deployment process. Included are the fin system, the clamp system, and the parachute system. Following sections detail the concepts, design process, and detailed design of each of these subsystems and the testing necessary to determine their performance. These items are closely related to the complete vehicle design but involved research and choices unique to the specific requirements of each subsystem.

5.1 Fin-Stabilized Projectiles and Concepts

The decision to use a fin stabilized vehicle led to extensive research into existing fin-stabilized vehicles, their design, and whether a similar system could be designed or incorporated into the WASP vehicle. Various fin concepts based on existing systems were proposed and presented to the team. This process led to the discovery of an existing fin stabilization system that suited the vehicle requirements and mission. Integration of this system with WASP reduced development time and effort that would have been necessary to develop a new system.

5.1.1 Current Designs

The initial research into existing fin designs began by consulting experienced personnel in the field and references listing vehicles in use that relied on fin stabilization [11]. The information explained existing designs and gave the team a way to compare new concepts to current practice. Some of these vehicles are listed in Table 5.1, along with the country of origin and the base concept for the fins.

Table 5.1: List of Current Operational Fin Configurations

Vehicle	Country	Concept Description
155 mm M7 12 Copperhead CLGP (Cannon-Launched Guided Projectile)	USA	longitudinally folded, flip forward fins
152 mm 3OF38 Krasnopol CLGP	Former Soviet Union	longitudinally folded, flip backward fins
76/62 CCS Course Corrected Shell	Great Britain	longitudinally folded flip forward delta fins

Table 5.1: List of Current Operational Fin Configurations

Vehicle	Country	Concept Description
9M119 125 mm Gun-launched Missile Round	Former Soviet Union	radially deployed square fins
TAAS - Israel Industries 105 mm M111 APFSDS-T	Germany	Fixed radial delta fins
3UBK12 100 mm Gun-launched Missile Round	former Eastern Bloc	flip out conformal fins

5.1.2 Concepts Development

Concepts were developed for WASP using existing fin systems as a starting point. Initially a requirement existed to maintain the standard length of a Mark 64 shell, which severely limited volume and material for fins. Since many of the existing fins were stowed folded longitudinally within the gun or shell diameter and flipped out radially along a pivot at one corner, much effort was made to fit this design into the standard length. This arrangement would require slots in the shell, exposing them to launch pressures and compromising structural integrity. As the components and layout of the flyer were developing it became apparent that very little volume within the shell would exist for fins to be stowed or for mechanisms to deploy them.

5.1.3 Conformal Hinged Fins

One initial concept used curved conformal fins that when stowed would lie around the circumference of the shell within the five inch diameter. They would attach to the shell by a longitudinal hinge in the base, allowing the fin to swing out from the shell and align with the air flow. Curvature of the deployed fins would result in a reduction of the effective area for each fin. Incorporation of the fins into the aft boat-tail of an existing Mark 64, as in the Shell-Enclosed Flyer concept, was the first design iteration. If placed within the sloped boat tail, the longitudinal angle of the fin hinge would result in a misaligned fin when deployed, actually causing rotation. Therefore it would be necessary to straighten the back end of the shell to accommodate the fin hinge, which would increase the drag of the shell. At that point in concept development reduced range from any increase in drag was seen as a big drawback. Pressure exerted on the fins and fin mechanisms during launch was also a concern, since the hinges would be directly exposed. Reduction in base outer diameter to fit the fin thickness would reduce the base area available for structural support of the flyer and projectile.

5.1.4 Conformal Spar Fins

A variation of the above concept was briefly researched, in which the fin was conformal to the shell diameter when stowed, but was deployed radially outward with an arm into the base. A boat-tail would still be possible for the back end and the fin deployment mechanisms could be located within the shell away from the launch environment. Vehicle length was not available at the time to fit straight radially deployed fins. An unprecedented concept would be difficult to pursue, and the effective area of the fins was small. Questions concerning whether deployment was quick enough and the possibility of jamming the deployment arm were sufficient enough to reject the idea.

The complexity of placing fins and a complete flyer within the current length of a standard shell was soon realized. The requirement to match the standard Mark 64 length was revised to simply keep the system length as short as possible. Design work had demonstrated that the flyer with all necessary components would fit into the length of a standard shell with very little margin and no spare volume available to store fins. This led to further research into the most commonly used fin deployment method; folding the fins longitudinally forward or backward within the gun or shell diameter.

5.1.5 SAL-GP Fins

During discussions with Draper Laboratories and exposure to the various projectile development programs, the Extended Range Guided Munition (ERGM) program was found to have fins that appeared to meet the vehicle requirements. The short configuration of the ERGM Demonstration Round used the projectile body of the Navy's Smart Active Laser-Guided Projectile (SAL-GP) program. These fins were attached to the SAL-GP projectile, which has a shape similar to a standard Mark 64 projectile and are launched from five inch Navy guns. The configuration of the ERGM Demonstration Round is shown in Figure 5.1 below. Dahlgren designers [29] were contacted and provided drawings of the fins and the fin hinge plate that attached to the shell. It was soon determined that with some modifications, and by lengthening the aft end of the base, the hinge plate design could be readily incorporated into the design of the back end, as noted in the previous section.

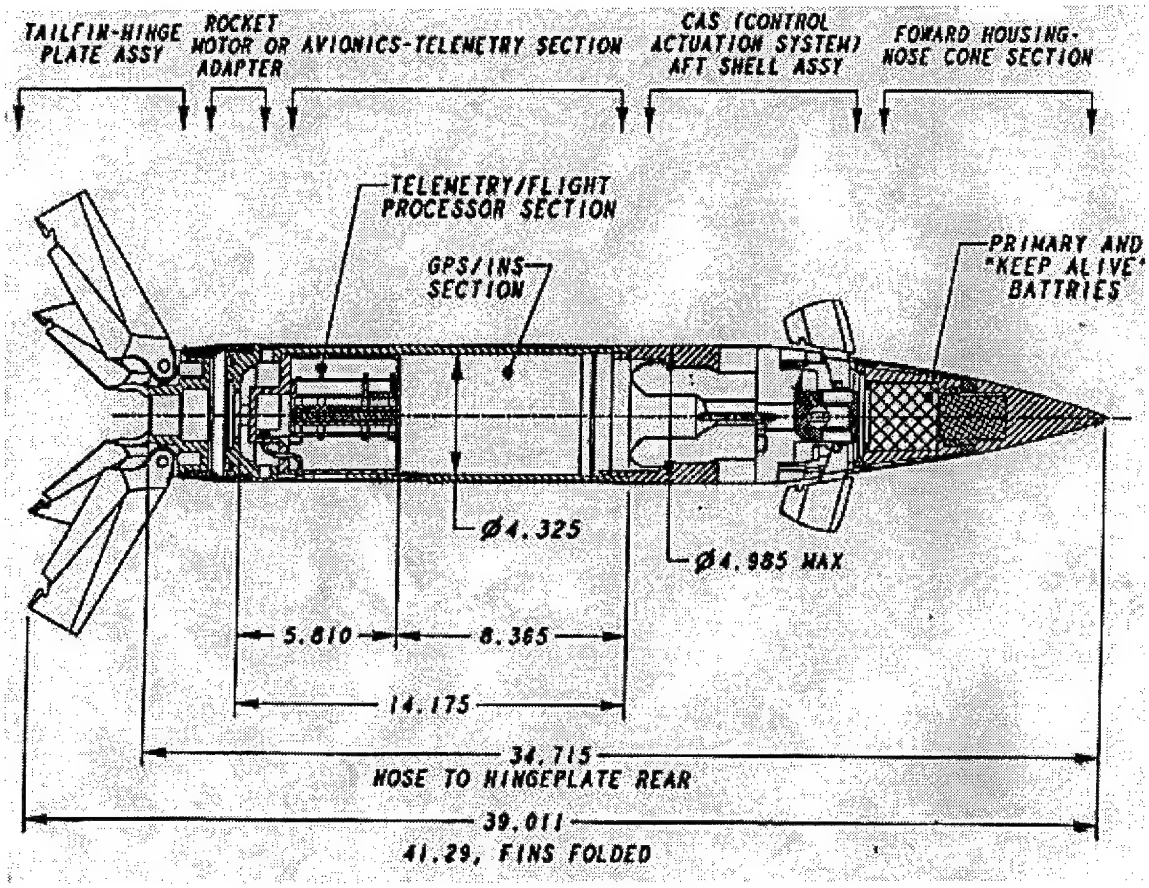


Figure 5.1: ERGM Short Configuration with SAL-GP Fins

Aerodynamic data was received from the Navy [30] and stability calculations confirmed that the fins would stabilize the vehicle, provided the c.g. could be placed accurately. The choice to proceed with the SAL-GP fins was made promptly following the determination that they would meet the requirements for the vehicle. Use of an existing system would require only simple modifications to the base design and reduce the development time for a new system. A test set of the fins for investigation and a flight qualified set for integration into a live fire vehicle were acquired from Dahlgren at no cost [29].

5.2 Analysis and Integration of Fin System

Stability analyses of the fins and the aerodynamic data helped to determine the necessary location for the c.g. This location was close to the location calculated using Pro Engineer, and the team was confident any adjustment necessary would not be complicated.

5.2.1 Aerodynamic Properties

Properties of the fins were received from contacts at the Navy Surface Weapons Center at Dahlgren, Virginia [30]. They listed the coefficients of drag, pitch force, and pitching and rolling moments for various Mach numbers. Data corresponded to the arrangement on the ERGM short motor configuration shown in Figure 5.1, and included values for the shell body and fins without the canards. Calculations of stability and range estimations can be found in Reference [31]. The data are attached in Appendix H.

5.2.2 Deployment Mechanism

The deployment of the SAL-GP fins does not involve any active mechanisms. A fin retainer and fin retainer plate are mounted around the inside trailing edges of the fins and hold the fins in during assembly, handling, mounting within the gun, and launch. A modified screw holds the fin retainer and retainer plate in the correct positions around the rear of the fins. The pressure forces of launch and the rebound force cause the modified screw to break, which releases the fin retainer and the fins. Examination of the test set of fins revealed that the fins are not pre-loaded to deploy outwards, and the team assumed that the rebound force causes the outward and forward deployment of the fins. As a fin reaches the correct deployed position, a notch on the fin axle area lines up with a spring-loaded fin stop pin beneath the fin axis. The clip springs out from the base, holding it in the deployed position. Some of these details are shown in Figure 5.3. More complete specifications, the engineering drawings for the current fin system are shown in Appendix G. Figure 5.2 is a model of the deployed fins and base assembly from two different views.

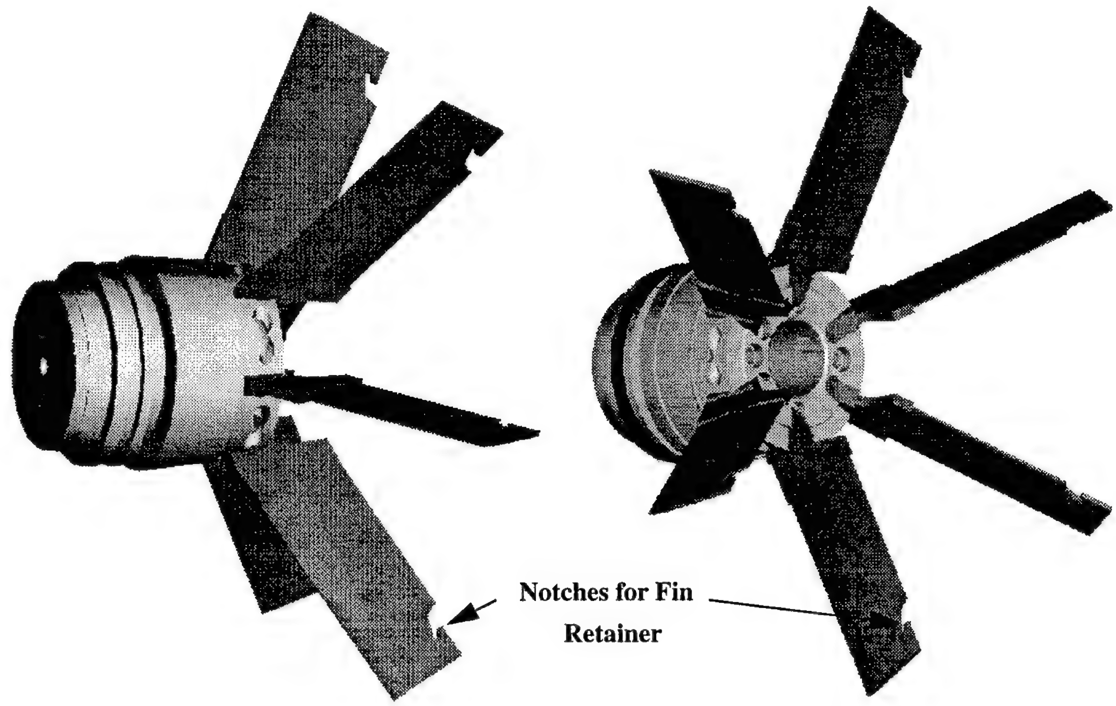


Figure 5.2: Two Views of the Base and Fin Assembly

5.2.3 Support Structure

Structural support for the SAL-GP fins is provided by a hinge plate that threads to the aft projectile body. The hinge plate aligns the fins to fold longitudinally with minimal clearance and the largest possible fin area. Each fin attaches to the hinge plate with an axle bolt about which the fin deploys. Each of the six fin axles are mounted through axle holes located through the base thickness close to the outside radius of the base. Six fin cavities equally distributed around the outside circumference provide clearance for fin mounting and rotation. This structure is shown clearly on Figure 5.3 below. The geometry provides maximum extension of the fins into the air flow around the shell body. Beneath these axle holes are longitudinal holes for spring-loaded fin stop pins. A small fin crush pin that helps to halt the fins deployment is located towards the outer circumference of the fin cavity. The axle holes, stop pin holes, and crush pin are included in the vehicle base design to ensure successful deployment and operation of the fins.

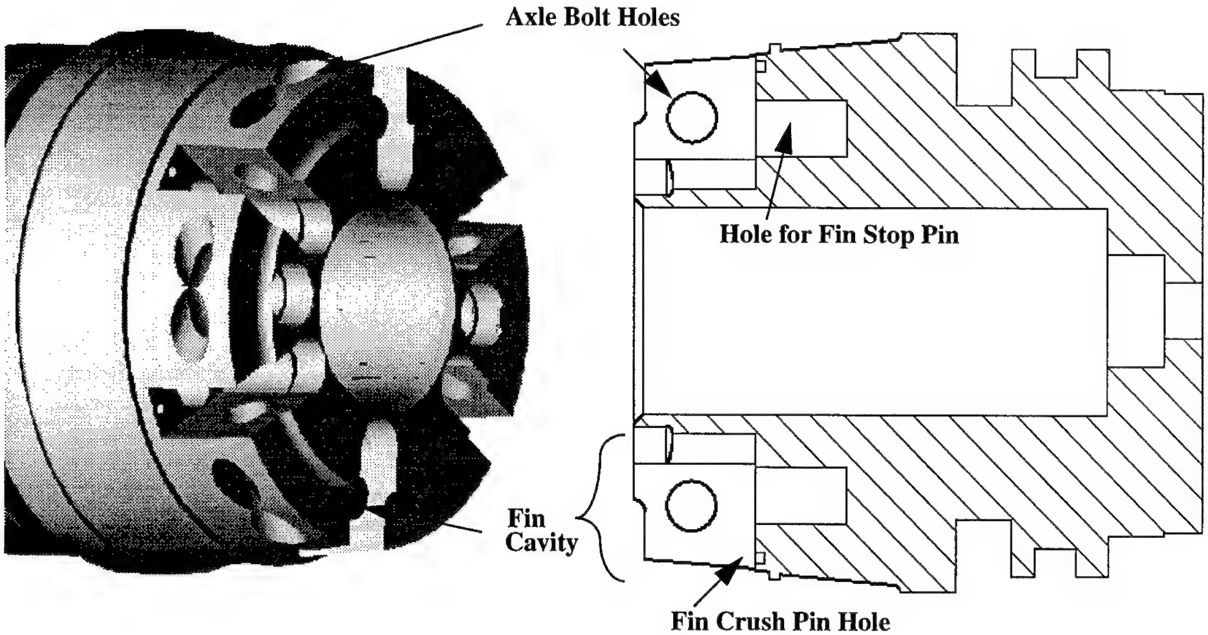


Figure 5.3: CAD Model and Cross Section of Fin Support Area

5.2.4 Assembly

Assembly of the fins for the vehicle prototype would begin with disassembly of current flight-qualified fins. Consultation with the engineers at NSWC Dahlgren to ensure correct disassembly of the fin system would be required. The assembled vehicle would use the same axle bolts, spring clips, fin stowage cap, and fins. Once the current fin set is disassembled correctly, it could be installed on the current base.

It would be possible to assemble the fins directly on to the base if the fins and their components were available prior to assembly to a SAL-GP hinge plate. This would reduce the work necessary for the fin assembly. Cooperation with the Navy's production facilities or fin suppliers would make this possible. For a production vehicle, or production of more than a few prototype vehicles, this procedure would save time and reduce the complexity of the assembly process.

5.3 Clamp System Detailed Design and Analysis

The clamp attachment concept was the best concept developed to meet the requirements of the WASP vehicle. Although based on the idea behind Marmon clamps, a similar clamp system

for projectiles was not found. Two half shells with ring protrusions on the inside insert into grooves in the base and the shell. Since no real clamping force is applied the use of the term clamp is somewhat misleading. The design does provide a tight, hard fit between the shell and the base provided the groove dimensions and tolerances are carefully controlled. Clamp length must match the dimension between the base groove and the shell groove when these two parts are assembled. Material on the base that inserts into the shell relieves the clamp of the lateral forces encountered during launch. Various methods for maintaining a tight fit of the clamps were proposed, such as hinges, axial pins, or cicumferential bolts. Currently the clamps are held around the projectile by two bolts that pass from the outside and across the clamp end, screwing into the other clamp, as shown in Figure 5.4. These bolts are placed within the material of the base ring protrusion which maximizes the possible bolt size. If necessary, the protrusion size could be increased by recessing the groove further into the base, allowing larger bolts. However the force load on the bolt is not fully determined, and testing under the actual loading conditions would be needed for that assessment.

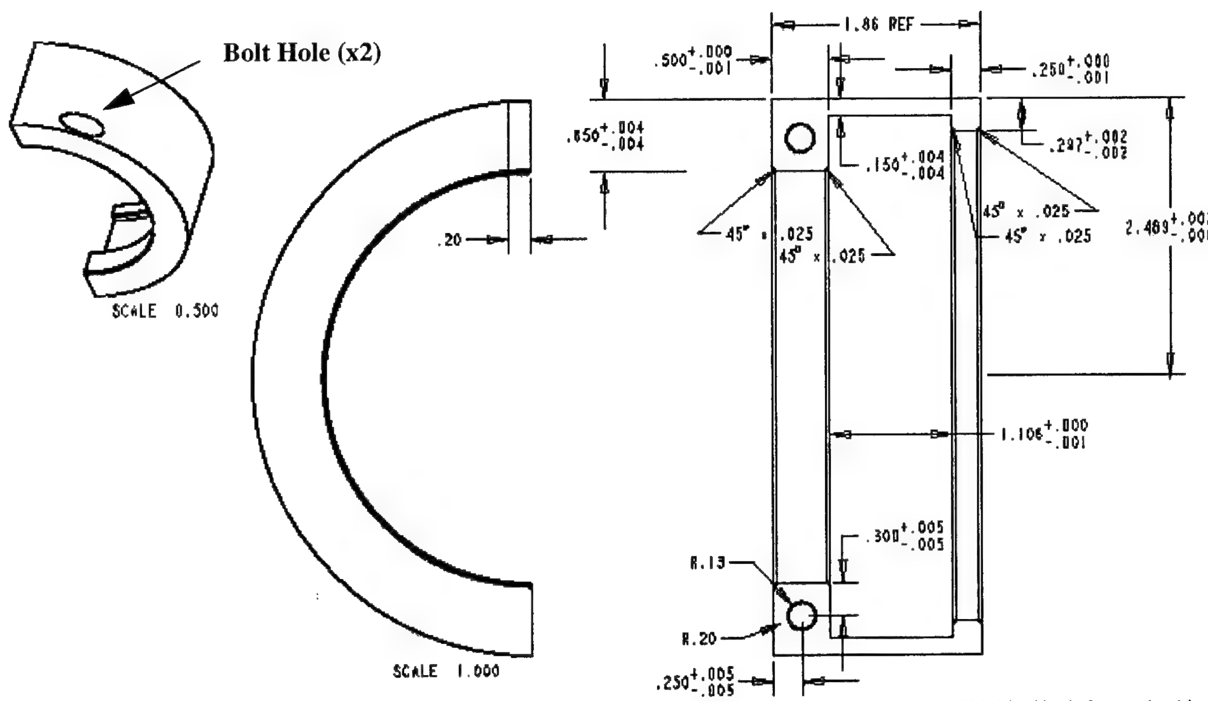


Figure 5.4: Detailed Drawing of Clamp

There are many advantages of this concept over the initial concepts. Assembly and disassembly are simple and repeatable. It does not require internal volume, since the charge that breaks the clamp attachment is placed on the exterior of the base. Tolerances around the clamp must be controlled very well and produce a very strong, tight fit. Parts were assigned tolerances that could be machined easily but assumed that at the worst tolerances the parts would just fit together. The resulting design involved straightforward lathe operations to machine. Requiring a tight fit led to some additional machining prior to successful assembly, but the extra work was minimal and allowed the fit to be exact.

The clamps are made of 17-4 PH annealed steel. This material was picked due to its use in the current fin hinge plate and the excellent strength characteristics of the alloy steel. They were machined in the machine shop of Draper Laboratory from the attached clamp drawing (Appendix I). Geometric constraints and analysis of the clamps allowed determination of the tolerances needed and exact geometry.

5.3.1 Geometric Constraints

As with all concepts, no material could extend beyond the five-inch diameter of the gun's internal dimension when launched. Shell thickness constrained the depth of the shell groove and the amount of material available for the clamp to grip on to. Initial design iteration allowed a groove depth of 0.30 inches, with the step at 0.15 inches (See Appendix F). This seemed to be too little depth for the clamp lip, and did not seem likely to survive. However with a shell thickness of only 0.5 inches, this depth was the maximum the geometry would allow. Removal of the far aft lip of the original shell left approximately one inch between the rear of the shell and the obturator. The width of the groove was arbitrarily chosen as 0.25 inches located 0.25 inches from the base. Detailed analysis using finite elements would determine whether these geometry constraints would be possible.

5.3.2 Launch Loads

Launch loads are applied impulsively to the structure, making exact material behavior difficult to predict. Constant loads equal to launch magnitude were applied for the boundary conditions and stresses were limited to the material yield strength. The area where the base and the

shell are mated supports the load path during the initial compression. In that phase the critical component is the shell, which could fail at the groove location. The clamps should only support rebound forces from the shell, estimated by Draper and Dahlgren personnel [9, 28] as four thousand times the force of gravity. The maximum force acting on the clamp in tension is the weight of the shell times four thousand. To add some margin to the model, a safety factor of 1.5 was used, setting the g-load at six thousand times the force of gravity.

5.3.3 Structural Analysis

The first analysis demonstrated that if the clamp were resisting the applied force with the clamp held at one groove surface, then the material would reach stresses beyond the yield strength by bending in the clamp where the material is thin. The clamp would have to be supported in some way with the tolerance and geometry, and use the design and geometry to avoid bending. With a tolerance set on the ability of the clamp to yield, as if the clamp were tightly fit within the grooves, the clamp material was still above the yield strength at the inside corners. Adding small rounds at the inside corners where the material was yielding solved this problem, and all of the clamp material was beneath the yield strength. The clamp itself should be able to withstand the impulse load of launch provided it does not yield for some reason during the initial acceleration or from lateral loads on the bolts. Research and experience with these devices did not indicate that there would be any forces acting on the clamp other than the lateral rebound acceleration. The final stress analysis shown in Figure 5.5 below is the last load case. Material deformation is exaggerated for illustrative purposes.

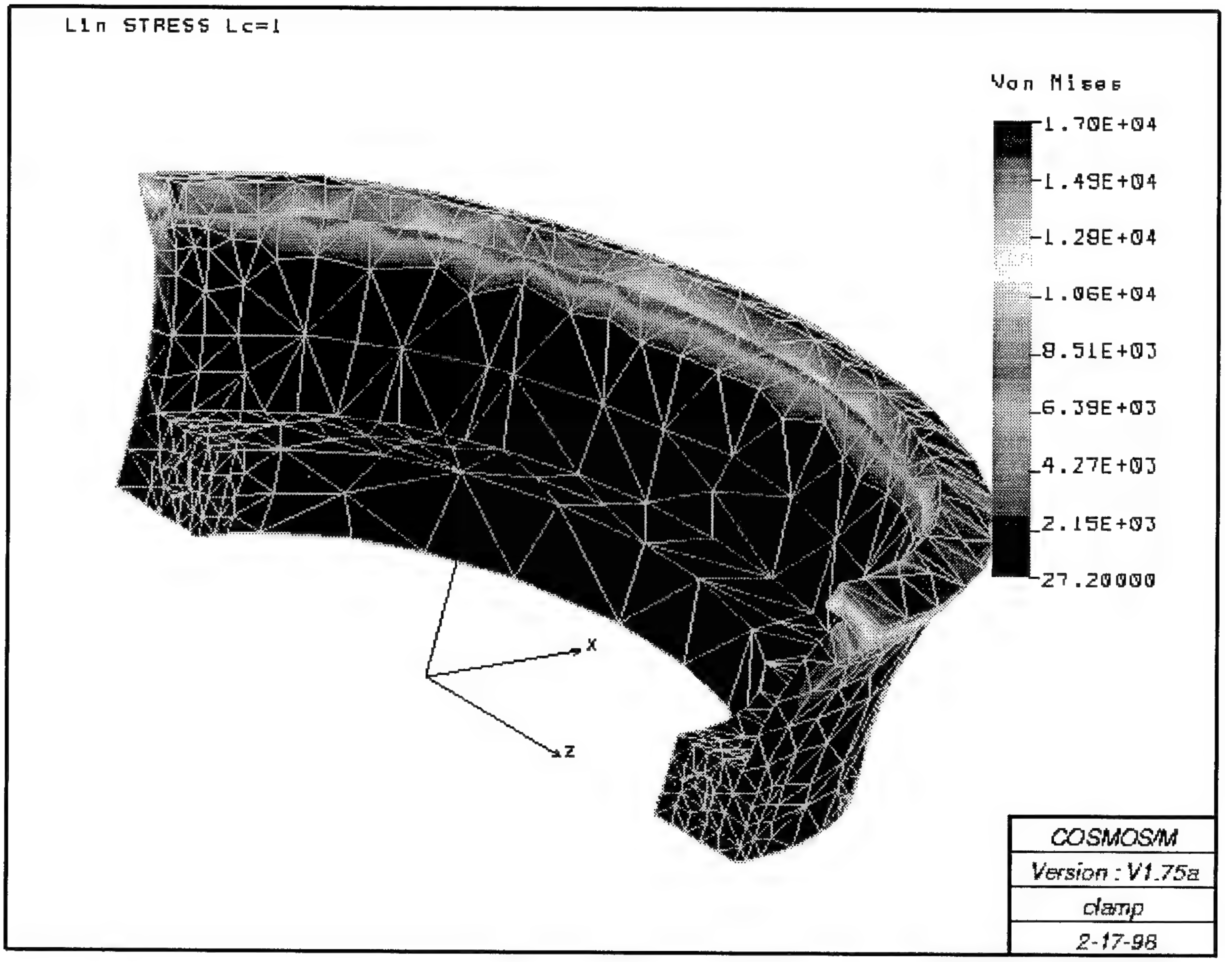


Figure 5.5: Finite Element Analysis of Clamp

5.3.4 Detachment Mechanism

Clamp separation is accomplished by using an explosive charge placed in the small groove beneath the clamp. The charge chosen to initiate separation was a Flexible Linear Shaped Charge. Linear Shaped Charges (LSCs) are hollow sheaths of metal containing high energy explosives such as RDX (Cyclotrimethylene Trinitramine)[32] specially shaped to provide directionality to the output energies. By taking advantage of the Monroe Effect, the explosive activation is designed to cut through adjoining material. The Monroe Effect refers to the jet of gas and molten liner material that is formed at the apex of a chevron shaped charge when activated [33]. This jet melts and cuts through almost any material in close contact with the chevron shaped metal sheath. LSCs take advantage of this effect to cut Marmon clamps and other devices on satellite separation

mechanisms. Flexible linear shaped charges (FLSCs) are similar except the sheath is made from combinations of flexible materials. This allows the charge to be curved or placed around a circumference. The operation principle is shown in Figure 5.6.

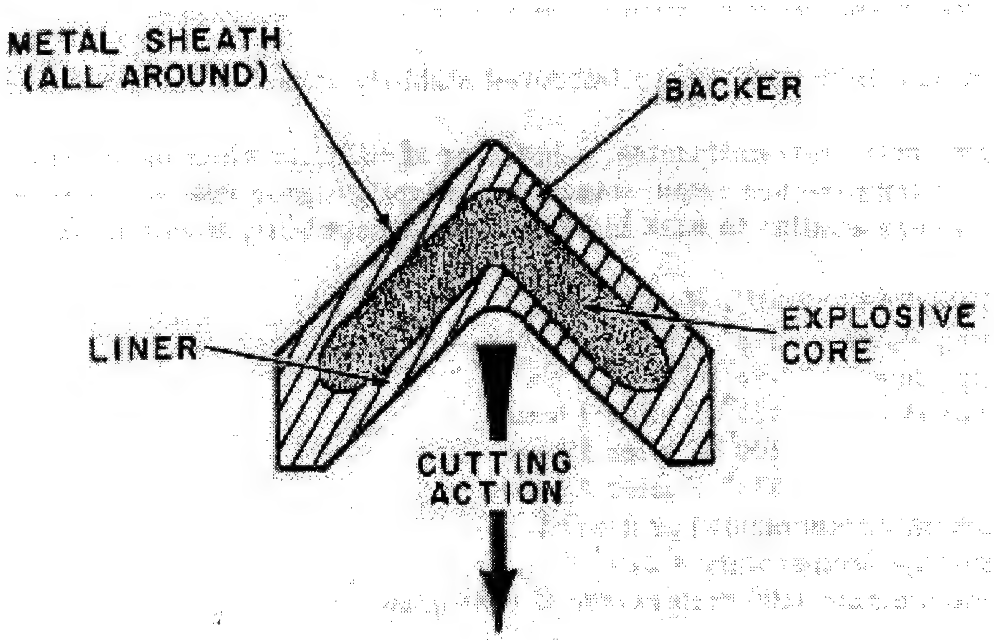


Figure 5.6: Schematic of Linear Shaped Charge Operation

A flexible shaped charge placed within the circumference of the base would provide the necessary cutting action to release clamps connecting the base and shell. The charge travels along the sheath at approximately 10,000 ft/s [34] which would result in almost instantaneous release of the clamps. There was sufficient material between the parachute cavity and the FLSC groove to place electrical connections and the actuation device. The Ensign Bickford Company provided information for the various FLSCs that they manufactured, and a design that met our geometry and materials was quickly found. The company was approached with a proposal to design the actuation and detailed placement of the FLSC based on the clamp system geometry and configuration. Engineers at Ensign Bickford recommended the use of a Mild Detonating Fuse (MDF) instead of a FLSC. MDFs produce high pressures within a recessed cavity instead of a cutting action. A mild detonating fuse cord within the charge cavity would produce enough pressure to break the clamp connection bolts in tension [32]. Schematics of the MDF and possible separation system configurations for MDF s are shown in Figure 5.7.

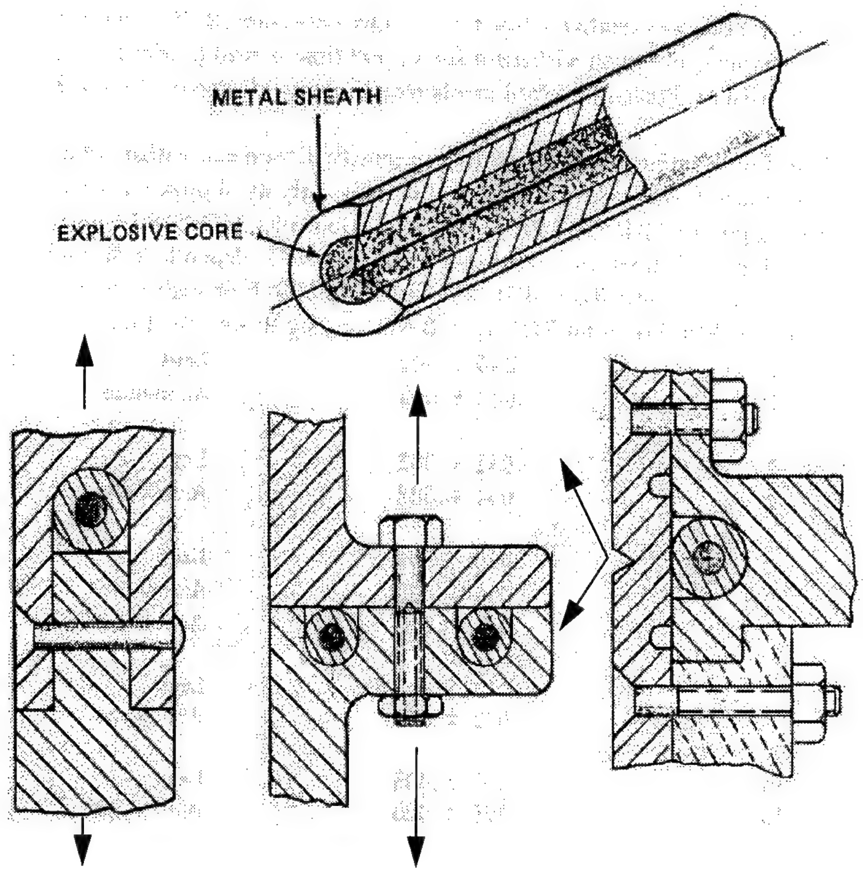


Figure 5.7: Mild Detonating Fuse Schematic and Separation Methods

Actual separation during a mission could cause some interference with the parachute or fin systems. Using a FLSC to cut the clamps could result in the forward portions of the clamp hitting the fins or a deployed parachute after they are cut. FLSC activation is not a "clean" process; it releases combustion products and fragmentation that can affect sensitive components [33]. Use of a MDF would cause the two clamps to be jettisoned sideways prior to deployment of the parachute. Behavior of the clamps at separation would be important to predict possible interference with the fins and parachute. Due to the possible interference resulting from FLSC activation, it was reasoned that it would be preferable to break the clamp attachments using a MDF. Forcing the clamp outward is likely to be safer than releasing debris. To ensure the parachute is not affected while deploying, separation should occur slightly before the deployment of the parachute. The behavior and effect of the mild detonating fuse on the clamps would be determined by testing and further consultation with experienced personnel at Ensign Bickford.

5.4 Parachute System

Successful deployment and operation of the parachute is a mission critical operation. The parachute system must have a reliable deployment system. Survival of the parachute during launch and successful deployment relies on the proper operation of the chute cover. The cover and its method of attachment was included in the design of the deployment system and is closely related to the base design. The parachute cavity provides a volume of approximately ten cubic inches and contains a one foot diameter parachute, swivel, and a plate attachment to the base assembly. During launch and ballistic flight this cavity is closed by the chute cover. Detailed design and arrangement of the parachute system is covered in Reference [31].

5.4.1 Purpose of the Chute Cover

The cover seals the parachute cavity from the gases and pressures of launch. Due to the shape of the fins trailing edge, there was space between the stowed fins and the cavity opening to place a chute cover. By controlling the geometry of the cover, it could be designed to force a cavity seal as it reacts to the launch gas pressure. The other purpose of the chute cover is to assist the deployment of the parachute. Current illumination rounds use the separation of the base plug to initiate the deployment of the deceleration chute. In this configuration, the cover alone is ejected at large velocity, initiating parachute deployment. By attaching the cover to the parachute with a line weaker than the parachute shrouds, the chute will be pulled out until the line and parachute shrouds are tight. The cover has enough ejection momentum to break the line when the parachute is fully deployed. Therefore the problem is how to attach the chute cover firmly to the base for launch and ballistic flight, and when commanded, separate from the base at high velocity.

5.4.2 Detailed Design

Since the cavity is located at the very rear of the back end, it is directly exposed to the pressure and combustion gases generated at launch. The cover is designed with a 45 degree slope and flat lip around the cavity opening. This seals the cavity when pressure is applied to the cover. A flat surface faces the parachute with a small loop for the deployment line to be attached to the parachute. Exterior dimensions of the cover are controlled by the clearance area between the rear

surface of the base and the stowed fins. A round, slightly domed shape extending to the rear provides thickness over the parachute cavity. The dome thickness is limited by the trailing edge of the fins when stowed. Two arms extend from the round central shape at 180 degrees to one another and attach the cover to the back end. This attachment must be strong up to the point of parachute deployment when the cover is ejected. The resulting design integration with the fins and base is as shown in Figure 5.8:

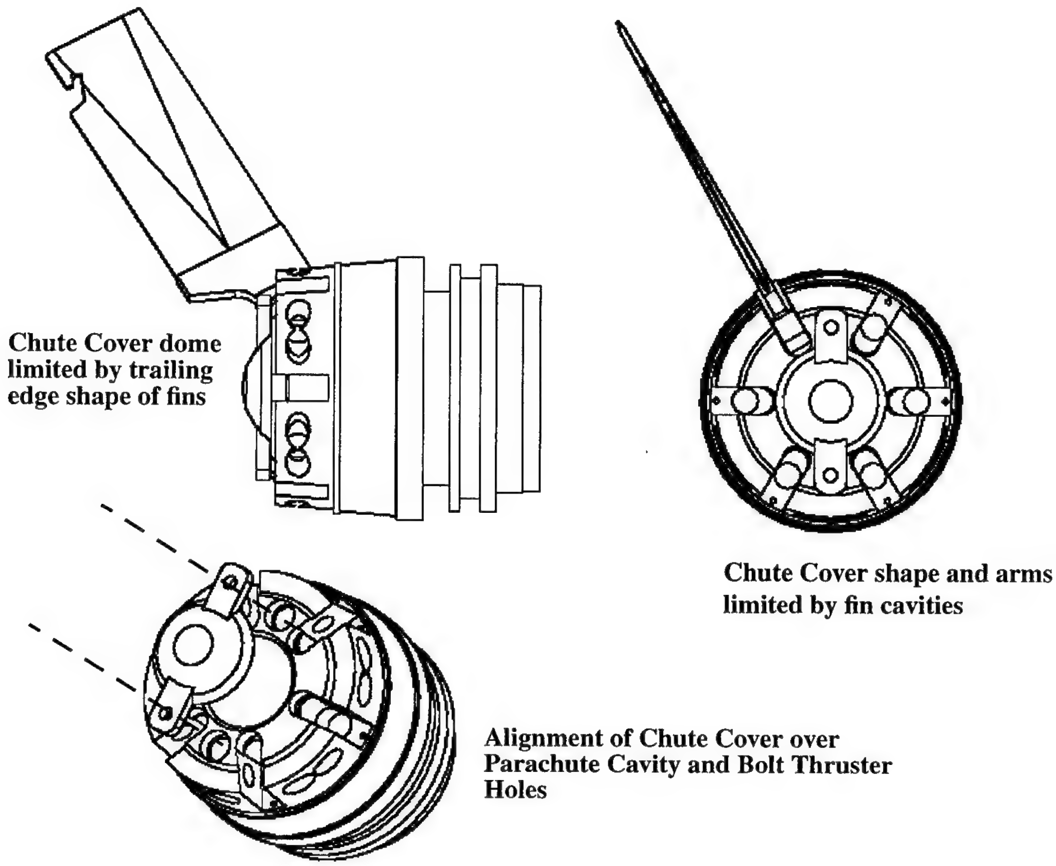


Figure 5.8: Integration of Cover with Base and Fins

During research into various explosives for the back end, methods to securely bolt items down and then thrust off with a large force were noted for possible use in the base. One method called a "bolt thruster" uses a modified bolt mounted in stationary material that shoots out a smaller bolt. The principle behind the bolt thruster is illustrated in Figure 5.9 below. Main parts of the thruster include the actuator (called a "squib"), the housing, the ejector, a piston, and shear and stop pins. A squib contains an explosive charge and is inserted at the base of the housing

behind the piston. At activation, the explosive generates pressure that pushes the piston against the ejector. The charge is sufficient to break shear pins securing the ejector to the housing. The piston accelerates against the ejector until it hits the stop pin. The ejector and any structure attached to it is continues to travel away from housing and structure it is mounted in.

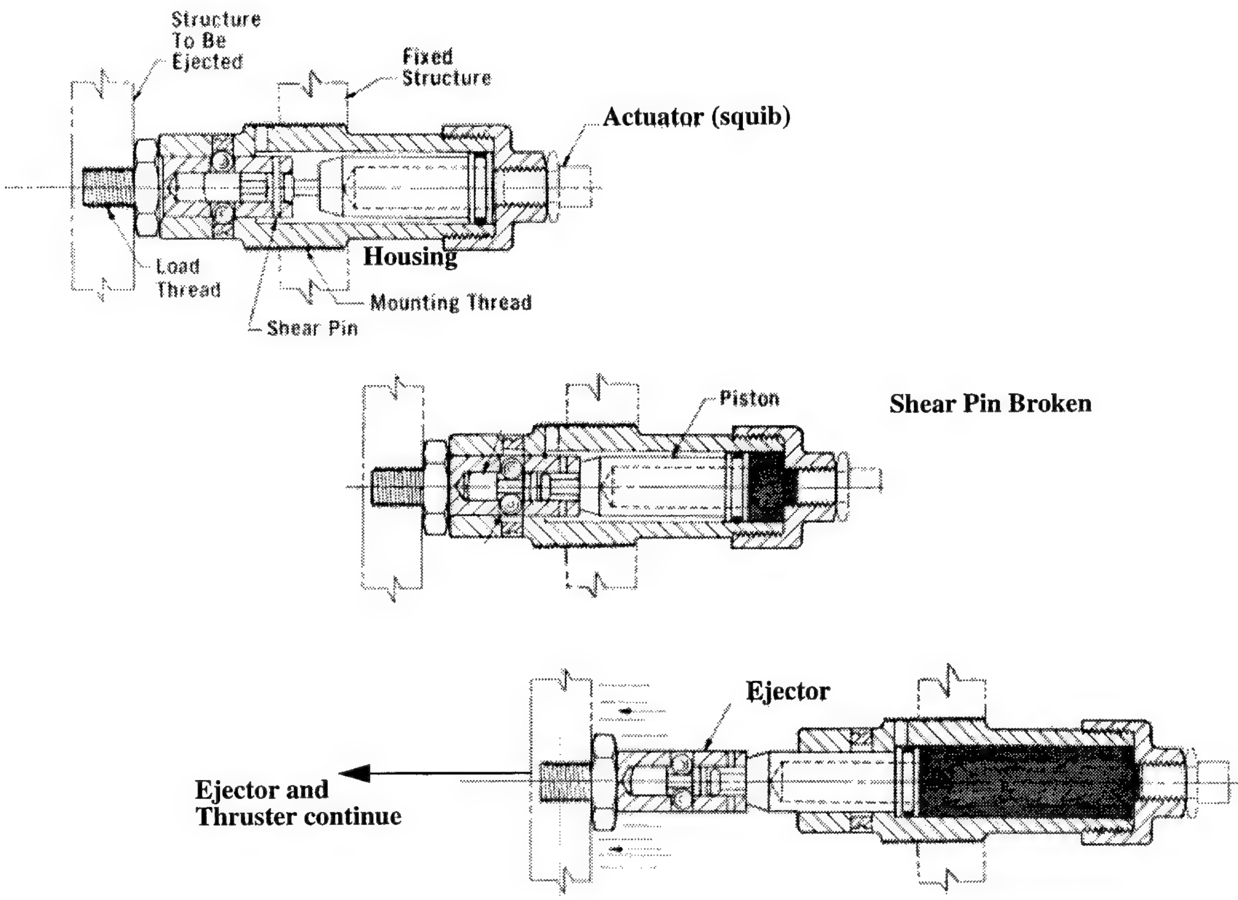


Figure 5.9: Schematic of Bolt Thruster Operation

Bolt thrusters are available in many configurations, but none found were able to meet the geometry requirements of the system. Upon further consultation with Special Devices, Incorporated, the company offered to custom build a thruster in the configuration needed for a reasonable cost and very quickly. The base and fin designs were sent to SDI with the geometry and limiting dimensions of the assembly. The chute cover required two attachments on either side in order to be securely held to the base, and these bolt thrusters need to be activated simultaneously for successful ejection. Special Devices Incorporated was able to design a bolt thruster specifically to

the requirements and geometric constraints within five weeks of the order. The bolt thrusters fit into the geometry shown below:

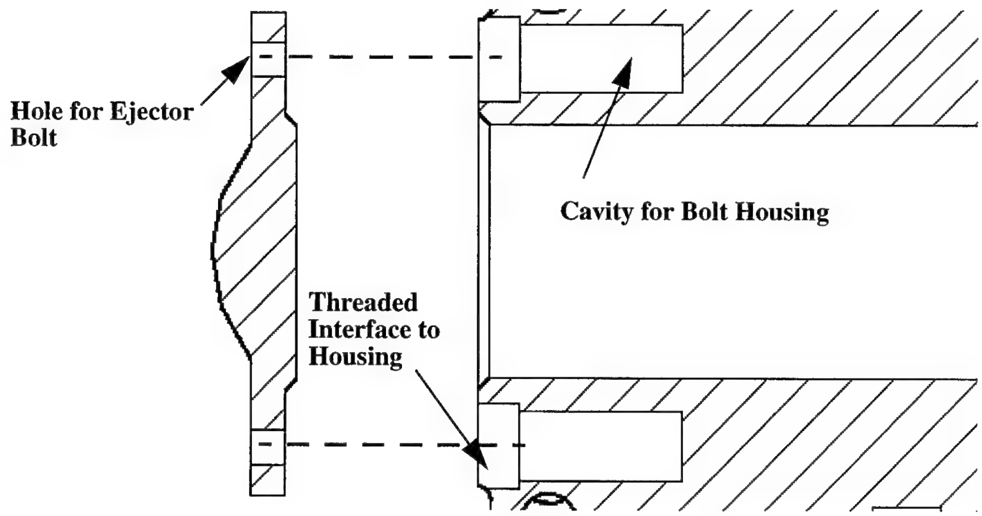


Figure 5.10: Cross-section View of Chute Cover Geometry

Detailed drawings are contained in Appendix G.

5.5 Deployed Systems Testing

Various methods were proposed to specifically test the performance of the deployed systems at each point in the operational sequence. Fin deployment testing was not necessary since it used a proven system identical to the existing system. Critical concepts to test are the clamp release, parachute deployment, and flyer extraction. Many methods to test the deployment were proposed, including a wind tunnel, static test, or drop from altitude. The most difficult variable to model accurately was the speed. At the time of deployment the vehicle would be traveling at transonic speeds. High-speed wind tunnel time was very expensive, hard to schedule quickly, and would not be likely to tolerate any explosive or release of parts into the flow. A static test at zero velocity would not provide significant data of interest for deployment at high speeds.

A drop test from a high altitude was proposed. The assembled vehicle with fins deployed would accelerate under its own weight until it reached a preset time or speed at which the deployment sequence would start. The owner of a remote control ultralight aircraft was approached with the idea and was willing to pursue it. But estimated altitudes necessary to reach a fraction of tran-

sonic speeds were too high for this approach. A jet aircraft or similar vehicle may have been able to accelerate the vehicle to the necessary speeds, but neither the time, budget, or test support was available to pursue this option. Therefore a separation test for the base was not possible, however it should be an integral step in a testing program to develop an operational vehicle.

Ensign Bickford quoted the price to design and test an integrated initiator, safety fuse, and mild detonating fuse placed into hardware manufactured and supplied by the project. Budget constraints towards the end of the program could not cover the quoted cost for this support, and a test of the explosive system did not occur.

6.0 System Assembly, Testing, and Projected Performance

A complete system could not be manufactured and assembled with the time and money available. The following sections describe the steps necessary near the conclusion of the project to produce a functioning test prototype of the High-G Vehicle. Some discussion for the development of an Operational Vehicle is also included. The predicted performance of an operational vehicle is also covered to further demonstrate the capabilities of the design.

6.1 Alignment and Tolerance Issues

The tolerance issues for the clamp were discussed above. Since the vehicle design involved the careful assembly of many different parts, tolerances were an important aspect of the design, especially when taking into account machine shop capabilities and increases in machining time to check fine measurements. Many of the components depended on a solid assembly to be supported structurally in the launch environment. This was especially true between the shell, base, and clamping mechanism and the wing system of the HGV. Another major challenge for the shell and base design was to fit the flyer completely within the shell and to support it effectively. Forward shell interior features had to match the dimensions and shape of the flyer to prevent the flyer from rattling within the shell and from slamming to the front of the shell upon rebound. Control of the blind interior machining process for the shell made exact measurements difficult to make. The base had to lie flat with the flyer rear which would maximize the ability of the base to

support the flyer. This was difficult because all current shells have tolerances that can make the geometry hard to align.

The rework required for each shell in the present configuration could be avoided if the tolerances for all designed parts are kept consistent. Since much of the alteration during the project occurred simultaneously with the design, and small changes were not always communicated effectively, some rework was necessary when assembling the system.

6.2 Air Gun Tests

Many tests were conducted in an air gun at Picatinny Arsenal in Dover, New Jersey. An air gun simulates the launch loads of a real gun by shooting a test canister at similar acceleration magnitudes. The actual acceleration versus time profile is sharper, because the air gun canister is accelerated much quicker. It reaches similar acceleration levels in three milliseconds as a real gun reaches in sixteen milliseconds. Despite this difference, the tests still provide good data for structural survivability. Testing occurs quickly, allowing for repeated tests with the same structure in the same day. Test canisters for the five-inch air gun are limited to a four inch inner diameter. This restriction prevented testing of the components for the flight support and deployment systems but allowed extensive testing of the flyer, wings, and propulsion systems. The testing of these systems is covered in References [21, 22].

6.3 Assembly for Canister Test

Canister testing was recommended by the engineers at Dahlgren when the team presented the project. A canister test refers to the testing method; a test item is placed within the body of an eight-inch diameter test canister shot from an eight inch gun at the Dahlgren testing facility. Figure 6.1 is a drawing of the test canister.

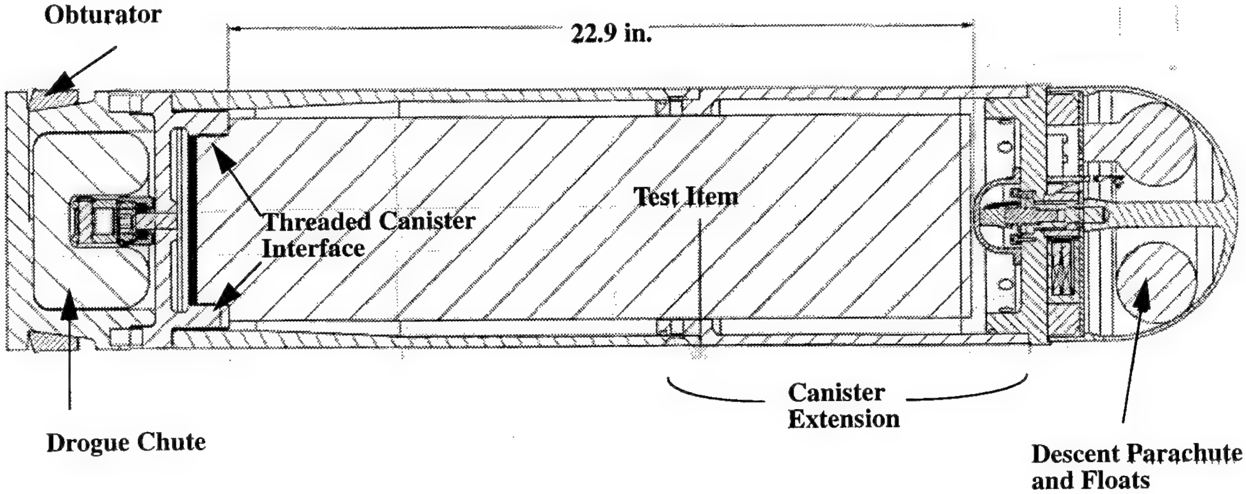


Figure 6.1: Eight Inch Test Canister

A test canister with two six inch extensions added to the body contained the entire vehicle without the fin system. Specific launch accelerations depending on the weight of the vehicle could be set by the amount of propellant loaded into the gun breach. The test requires at least a week of assembly preparation, cannot be repeated on the same day, and costs significantly more than air gun tests. Canisters are retrieved from the test range, so the flyer and components tested would not be lost.

Canister testing simulates a real live fire test except for exposure to the gun barrel surface and the combustion gases and pressure. The accelerations and energy imparted to the test item are nearly identical to the acceleration profile of a real five-inch gun, and the Dahlgren personnel felt that the vehicle would not have problems surviving actual launch if the canister test was successful.

Due to the test item mounting structure, the exact aft structure of the vehicle could not be tested. Test items are mounted by threading onto the interior base of the test canister. To mount the WASP vehicle a modified base that excluded fin support and obturator geometry had to be designed. Base design from the clamp groove forward did not change. The threaded interface to the test canister was placed aft of the groove. An identical parachute cavity was kept within the base structure to allow flyer attachment and to simulate the base structure, but no parachute assembly was inserted. Despite the changes major structural aspects of the base design could be

tested, especially the unprecedented use of the clamped concept. Since the fin and obturator geometry is identical to a system currently in use, these components should not have a problem with launch survival or operation. The modified base is shown in Figure 6.2.

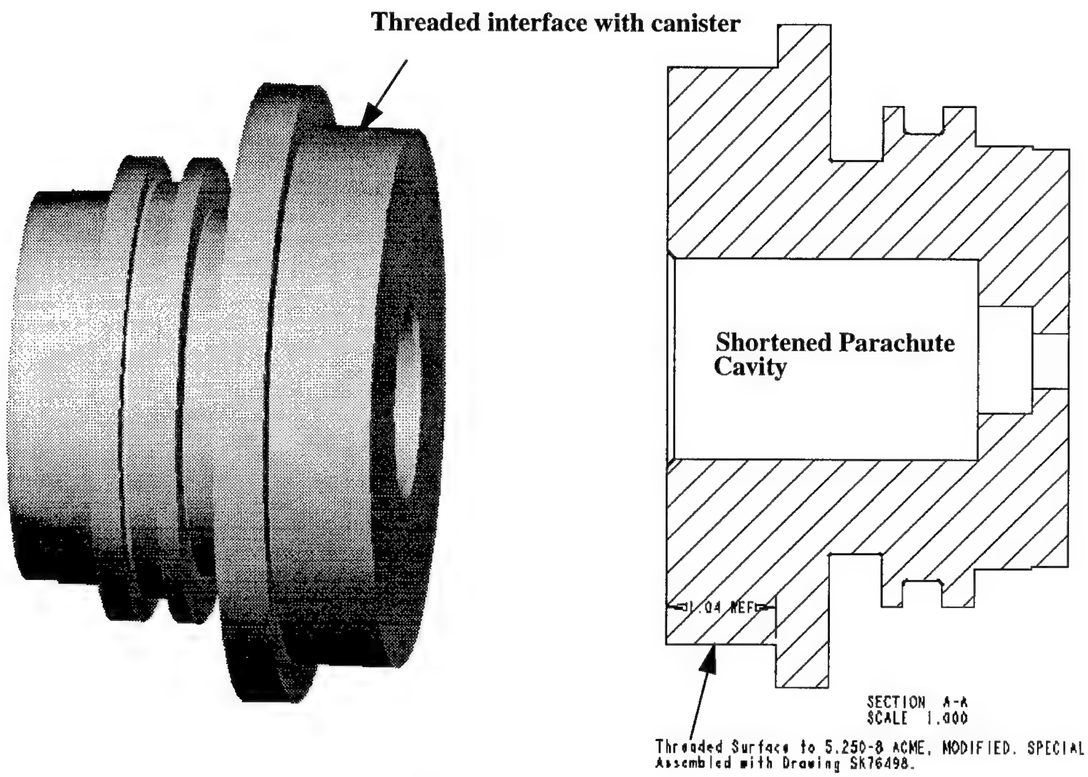


Figure 6.2: Modified Base for Eight Inch Test Canister

To reduce the lateral forces on the test canister base, test personnel recommended the addition of a lateral nose support at the forward end of the test vehicle. Their recommendations combined with the geometry available in the nose of the shell near the propeller fork led to the nose lateral support shown in Figure 6.3.

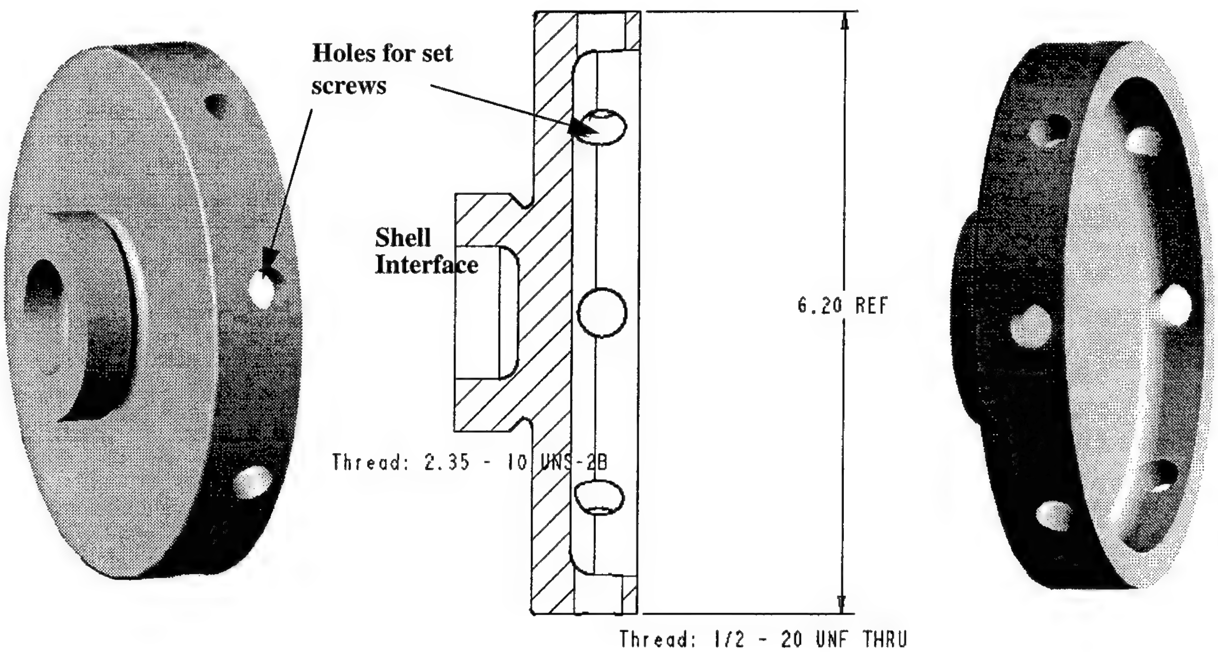


Figure 6.3: Lateral Nose Support for Test Canister

Using analysis codes at their facility, designers at the Dahlgren test range approved the design. Made from 7075 aluminum, the lateral support was manufactured by the Draper Machine Shop. Eight holes on the outside lip of the support are threaded to hold one half inch set screws which are screwed down to just contact the canister walls. This support holds the nose in place laterally but allows axial motion. Weight of the support was within a pound of the projected weight of the nose cone, applying a similar load to the shell nose.

Preparation for the test canister proved to be the only instance that the flyer and shell systems were assembled completely. When the test base, flyer, and shell were assembled for the canister test, the flyer protruded 0.09 inches farther than designed. Corrections made to the shell caused the flyer to be closer to the base of the shell than expected. Modifications to the base and flyer interface were made to fit the flyer securely instead of the propulsion module. It was originally thought that the propulsion module of the flyer would be altered if the system did not assemble correctly. Inspection of the final parts indicated that it would be much simpler to adjust the height of the base protrusion into the shell. Base modifications were done by the team in the department's machine shop prior to shipment of the canister to the testing facility. Modifications to the clamps had been done immediately after manufacture, and were easily assembled to the

flyer and shell system. The nose lateral support was screwed into the shell nose fuse threads. All flyer components were stowed, the flyer inserted into the shell, and the clamps added. This test canister assembly was modeled and assembled on Pro Engineer prior to part manufacture to check clearances and mass properties (Figure 6.4). Two photos of the assembly parts show the test items before they were sent to the Dahlgren facility (Figure 6.5).

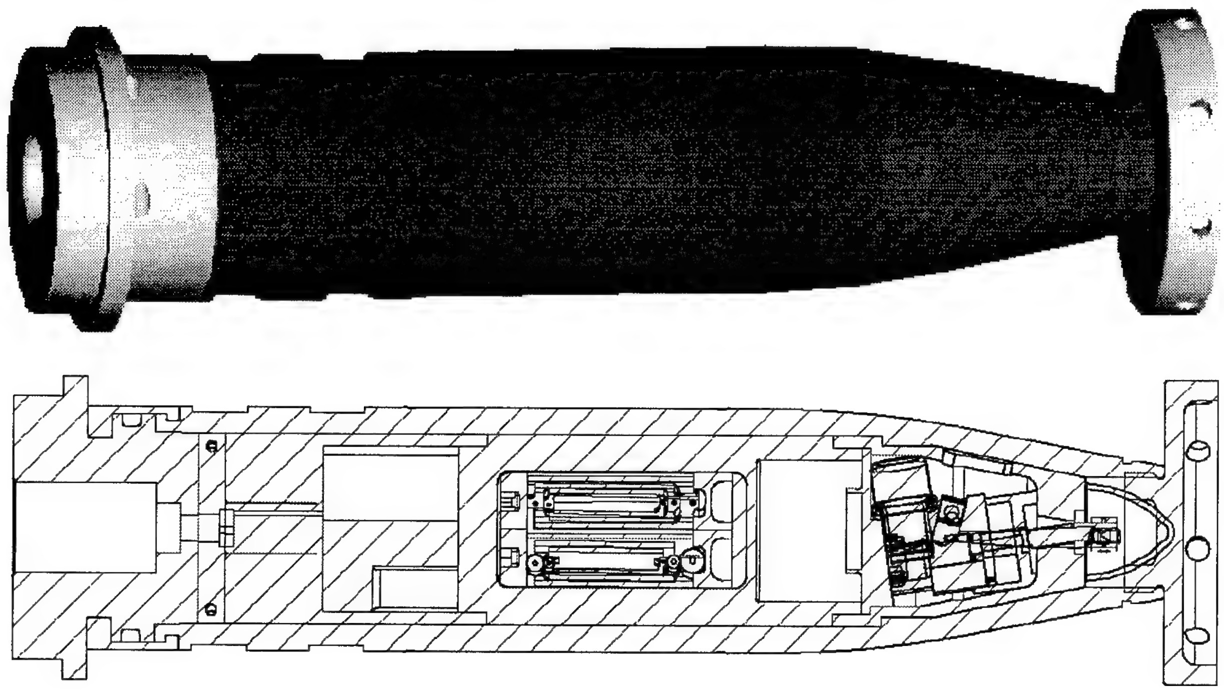


Figure 6.4: Assembly of Test Vehicle for Eight Inch Canister Test

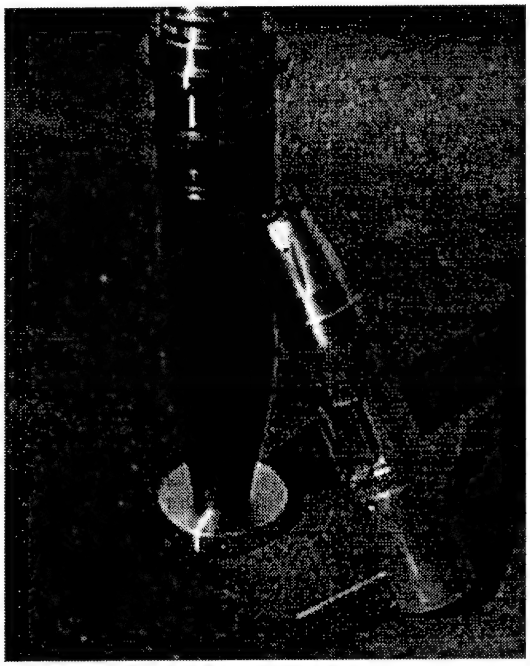
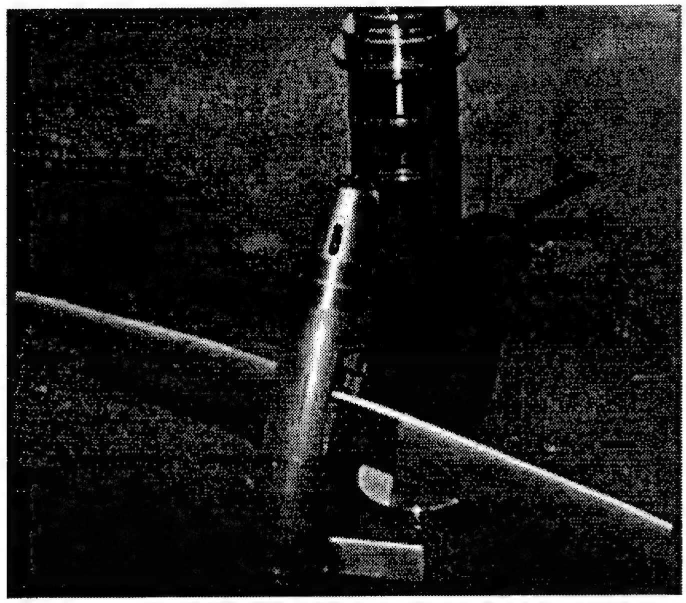
 

Figure 6.5: Test Vehicle Prior to Complete Assembly of Flyer

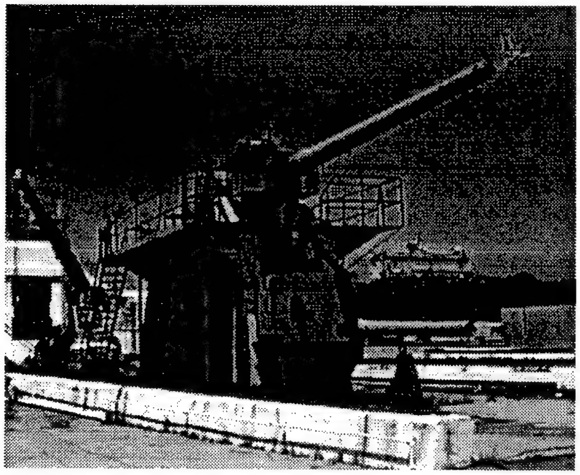
The test vehicle was shipped to the test facility in Dahlgren, Virginia. At Dahlgren, the engineers added Loctite to the external threads, including the lateral nose support, the clamp bolts, and the modified base threads.

6.4 Canister Test Results

Canister testing took place on May 14, 1998. Testing was conducted on the same day that Raytheon was testing components for a similar concept vehicle. Combining testing on the same day reduced the cost but did not allow choice of testing dates. Testing had been scheduled for two weeks earlier but was delayed. The WASP system had been sent to the Dahlgren test site in late April for assembly and integration with the test canister. Personnel assembling the canister and test item checked the tightness of all the threaded joints and added Loctite to ensure a secure thread grip. Assembly with the test canister proceeded smoothly due to the communication with

the Dahlgren contacts [35], and the test vehicle was ready to be fired inside the eight inch test canister.

Figure 6.6 contains two views of the eight inch gun. For canister testing it is elevated to a 75 degree elevation to reduce the canister range and simplify retrieval.



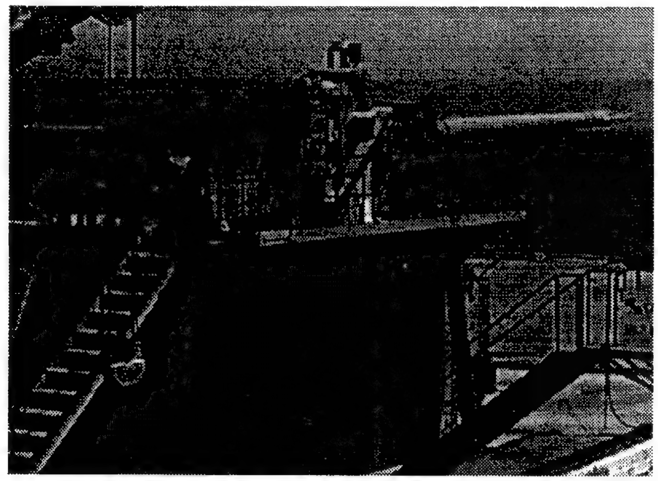
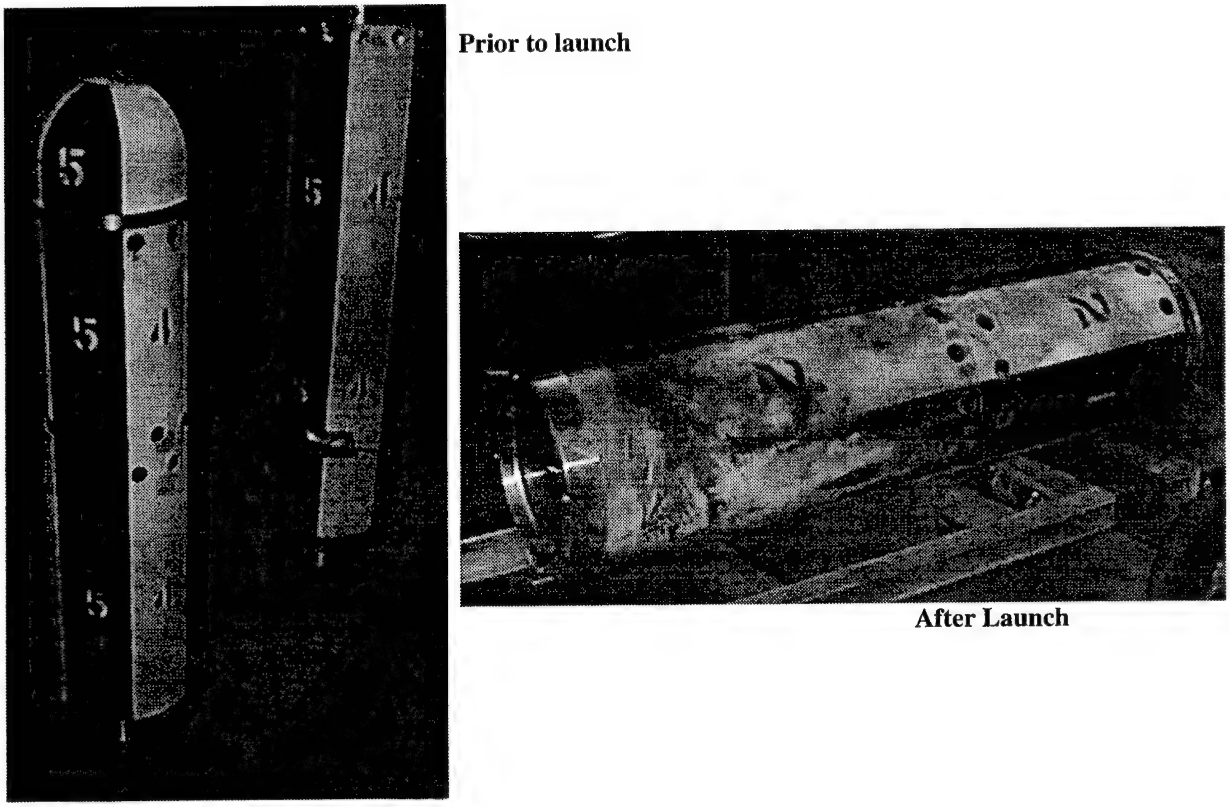


Figure 6.6: Eight Inch Gun at the Naval Surface Warfare Center Dahlgren Division

The canister was assembled and prepared for gun launch. It is loaded by hand into the gun breach, followed by the propellant canisters. After elevation to 75 degrees, the gun fired the canister. Measured acceleration on the assembly was 12,026 g's, the same acceleration magnitude seen by standard five inch projectiles. Rebound was not measurable but does occur in a similar fashion to standard guns. Launch and the failure of the canister drogue chute (a common occurrence) boosted the canister to an altitude of 7,700 feet, where the canister chutes deployed, and the canister fell into the Potomac River. Retrieval of the test canister occurred soon after. Views of the canister before and after launch are shown in Figure 6.7. Video of the launch and retrieval was recorded by the team members present [36].



Prior to launch

After Launch

Figure 6.7: Photos of Test Canister Before and After Launch

An initial inspection of the vehicle was performed on-site following canister retrieval and the conclusion of all tests. No external damage was seen as the vehicle was initially removed from the canister. The shell, nose lateral support, and clamp system were all intact and assembled exactly as they had been prior to launch. Removal of the clamps was easy, and the flyer was removed to examine the deployable components. Tail surfaces immediately deployed upon extraction from the shell and after removing the structural supports, the wings folded out perfectly. Detailed views of the assembly, clamps and the deployed flyer are shown in Figure 6.8.

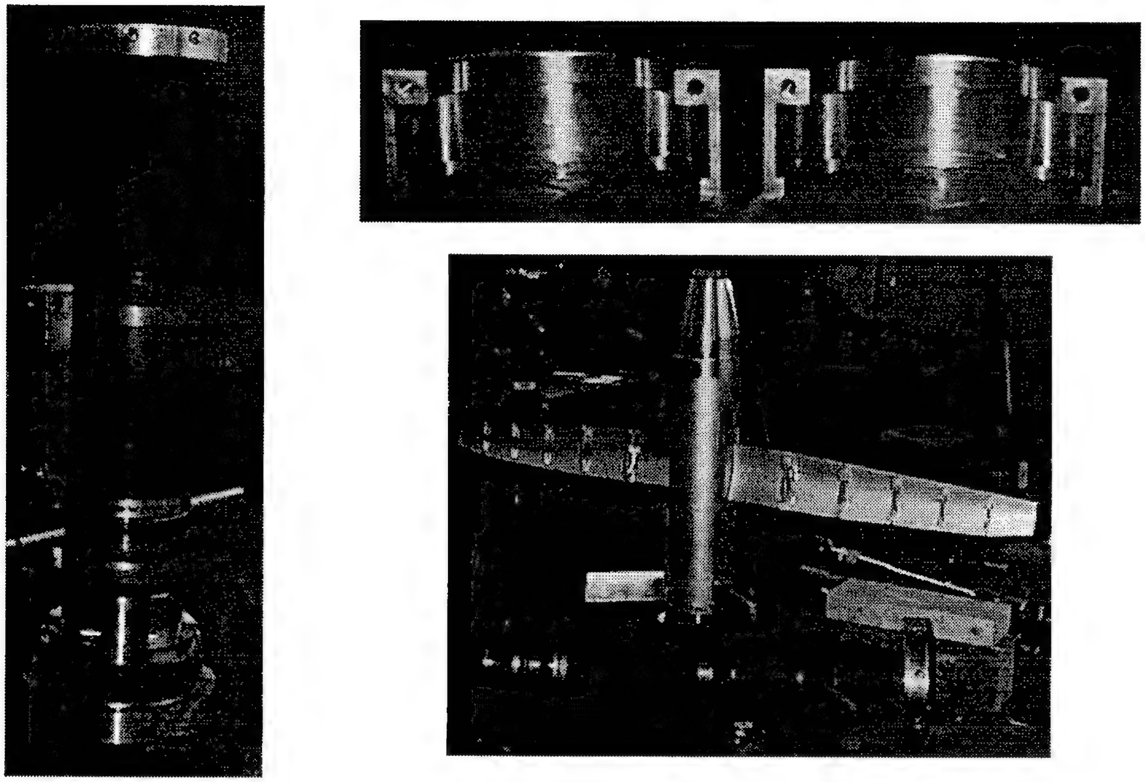


Figure 6.8: Photos of Test Assembly and Components Following Canister Test

Canister testing demonstrated the structural capabilities of the vehicle design. It was the first test for the clamps and the overall flight support system, and both functioned as designed. After detailed inspection, no cracks or deformation was visible on the clamps, base, or shell. The flyer and its components all survived; the wings deployed, the flyer control surfaces and servos were movable, and the engine retained compression of the shaft. Tests on engine performance were unable to be performed, but the engine shaft did rotate and no failure of the engine parts occurred. Based on the results of this test the flight support system and flyer can survive launch in a standard five inch gun.

6.5 Assembly of Flight Support and Deployment Systems

Final assembly of a prototype vehicle would be more complicated. A complete base would be a larger and more complex component with more attachments to be assembled and checked out prior to launch. Assembly of the flyer is covered in [21] and is assumed to be ready in the following description. Flyer preparation for flight would include structural assembly, ini-

tializing electronic systems, and ensuring safe connections for the explosives to the timer and fuse. After completion of these tasks, assembly with the flight support and deployment systems can begin.

The slip obturator would be the first part assembled to the base. Due to the solid band shape, it must be stretched to fit over the groove edges and to seat tightly around the base. To stretch the obturator, it must be heated by immersion in boiling water prior to assembly. This expands the nylon and allows the ring to be slipped over the aft end of the base and into the sloped groove for the obturator. As it dries and cools, the nylon shrinks back down to form a tight clearance with the base. With the obturator installed the remaining components are assembled with the base.

The bolt thruster and clamp separation charge would be assembled next. The wiring for each mechanism has to be passed through the base side and up to where the base connects to the flyer. All wiring from the base to controls in the flyer must pass through this area. Unfortunately the exact arrangement and connections necessary was not determined- but the team and Draper Labs have experience designing electrical connections under launch loads. Wires under the acceleration of launch cannot support their own weight, and need to be encased in epoxy resin. After the wires are passed through the base and the components successfully assembled, the resin would be applied to the wire paths and allowed to dry.

The physical mounting of the clamp separation charge was not determined. Personnel at Ensign Bickford have extensive experience with the design of these systems, and the mounting structure would have been included in their design of the actuation system. This design process however was not completed, and the exact mounting procedure is not known.

Assembling the bolt thruster involves simply screwing the thruster into the attachment area of the base after the wires are fed through. Matching 0.625-18 threads between the thruster and bolt thruster holes is included in the design. The bottom plane of the ejector bolt sits flush with the aft plane of the base. Tightening of the housing mount would be accomplished by tightening the ejector bolt protrusion if necessary.

Next the base should be attached to the flyer itself. Wire connections can be made to the circuits and controls within the flyer. The connections must be done carefully since they activate explosives that could be dangerous if not wired with the proper safeties. Once the wires have been connected and secured to survive launch, the explosive bolt protruding from the flyer tail

module is inserted into the base parachute cavity. A nut is placed within the parachute cavity and tightened over the bolt. The nut is tightened until it is flush with the remaining diameter of the chute cavity.

Assembly of the remainder of the parachute system can proceed after attaching the base to the flyer. The parachute plate, with the swivel and parachute attached, can be inserted into the parachute cavity and screwed to the cavity front surface. It is designed to fit over the nut of the explosive bolt. The parachute is then folded up by hand and inserted into the parachute cavity.

Chute cover assembly should occur prior to the assembly of the fins to the base. If the fins are in place while the chute cover is being assembled, it will make the cover difficult to reach and to tighten correctly. Ejector bolts from the two bolt thrusters should protrude equally at axisymmetric locations to the parachute cavity. Holes in the chute cover's arms line up with the bolts extruding from the base. The chute cover is placed down over the cavity, until the arm bottoms are flush with the rear of the base. While holding the cover flush, two nuts are added to the ejector bolts. These bolts should be screwed down over the chute cover to a tightness slightly above that used on the bolt thrusters themselves. Securely tightening does not affect the operation of the bolt thruster, since the entire ejector is thrust from the base with high velocity regardless of the nut tightness.

Assembly of the fins occurs next following the secure attachment of the cover. Springs and spring clips are inserted into the holes beneath the fin axle areas. Crush pins are inset into the small holes on the outside lip of the fin axle area. The fin is inserted into the area and pushes down on the spring clip until the axle lines up, and the axle bolts are inserted through the holes and tightened. Each fin is attached in a similar manner until all six fins are successfully assembled. Correct alignment of the fins may be necessary and should be done in consultation with the fin designers. Finally the fin retainer is inserted between the fins and into the trailing edge notches, the retainer plate is placed over the bottom of the fins, and the modified screw is tightened between the retainer and plate.

To complete the assembly of the complete system, all components must be attached to the projectile body. With all mechanisms stowed, the base and flyer assembly is carefully inserted into the projectile body. Clamps are then placed into corresponding grooves in the shell and base, and tightened together around the connection plane with the bolts. The nose cone for the shell is screwed into the cavity at the nose ensuring that it does not interfere with the propeller or the pro-

peller spinner. Figure 6.9 is a schematic flow of the assembly process for the base. Assembly drawings of the entire assembly (with fins deployed, not folded, and without some connections and obturator) is shown in Figure 6.10.

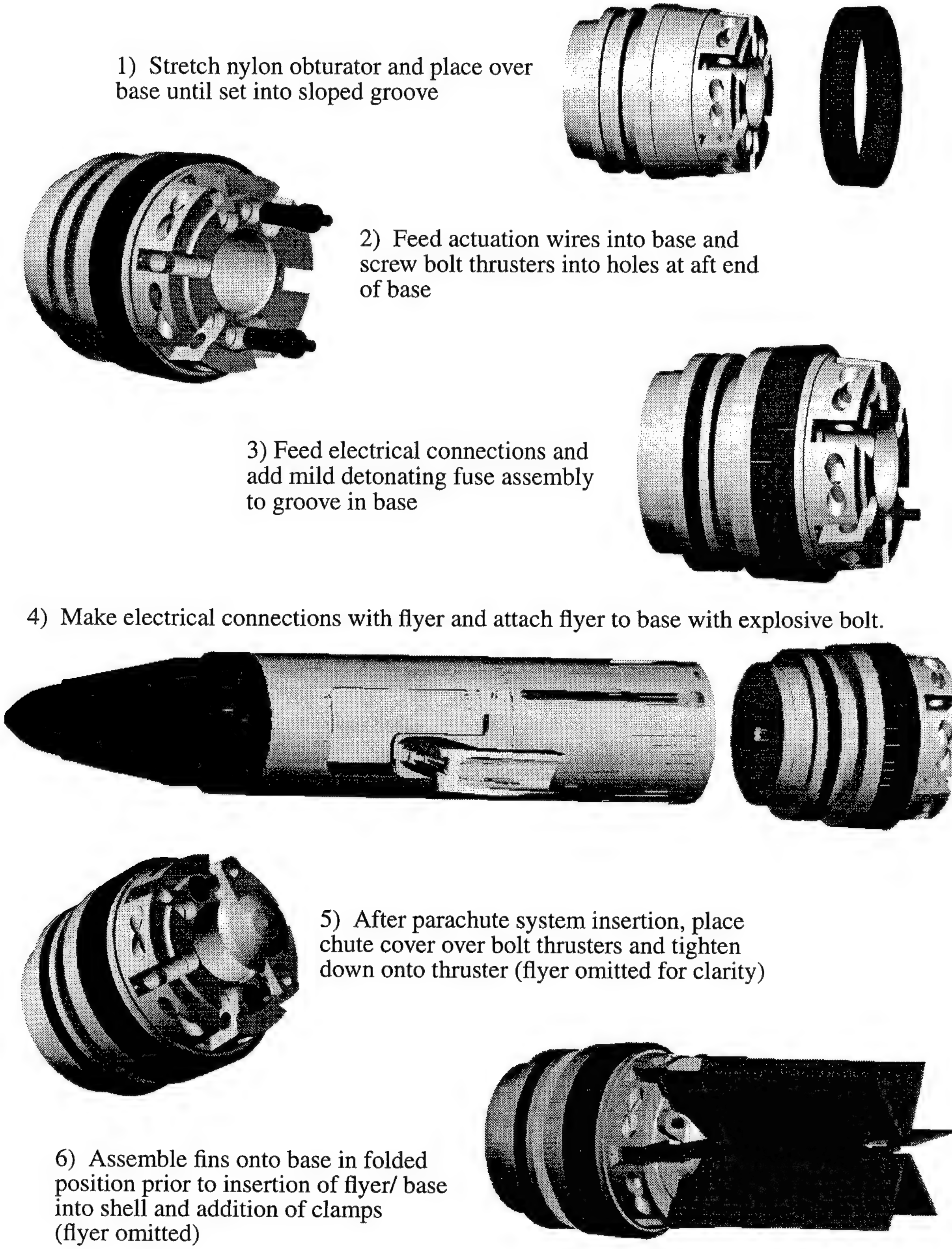


Figure 6.9: Schematic of Assembly Process for Gun-Launched Vehicle

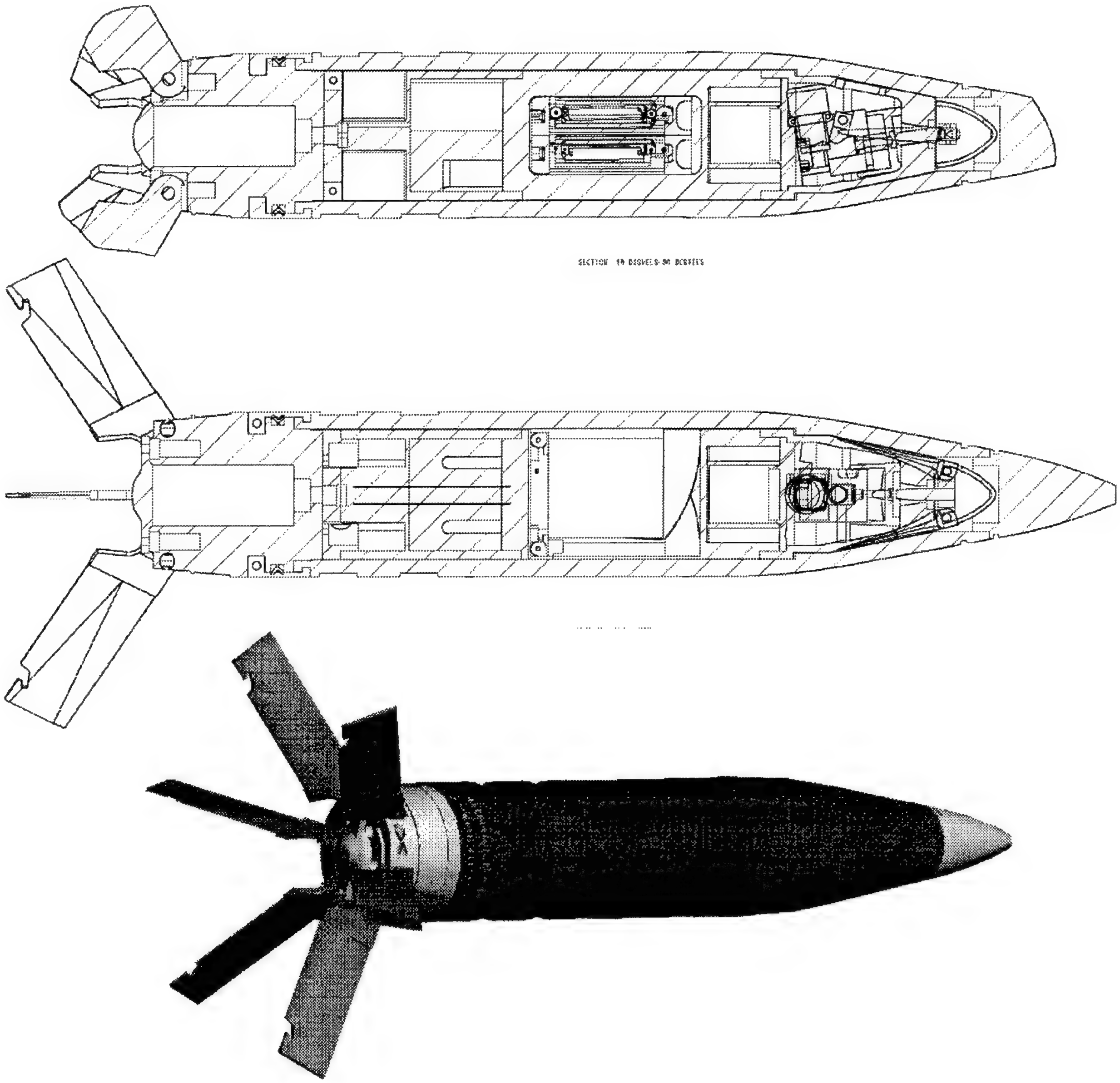


Figure 6.10: Cross Section and Model Views of Assembled Vehicle

6.6 Preparation for Launch

After assembly of the flight support system and the successful wiring of the deployment systems to the flyer controls, no additional preparation for these components is necessary. At this point the vehicle should be ready for launch from a standard five-inch gun.

6.7 Live Fire Test

Originally the project's goal was to fire the entire vehicle out of a five-inch gun at Dahlgren and test aspects of the deployment process. A visit to the test facility in the summer to gather information about testing facilities revealed challenges to receiving permission for a full gun test [7]. The most stringent requirement was to convince the test personnel that test items had a one in one million chance of landing outside the test range, a long river lined by private property. At a second visit this was difficult due to the complicated deployment sequence, unless that sequence occurred at a very low altitude. Personnel also felt that a canister test would be more useful since the launch support system had yet to be tested. A live fire test does not allow the vehicle to be retrieved, which was undesirable since the only data then available would be the high speed photography of the launch and flight. Prior to the canister test decision, the live fire test was designed to test many aspects of performance, including the structural integrity of the individual components assembled as an entire vehicle. Yet if the structure had failed, then the deployment process would not be tested, and the shell and flyer would likely be destroyed. With the decision to proceed with the canister test to test the structure, it was proposed to test the deployment process using a dummy flyer. Due to the cost of a live fire test, further design and testing work for the explosives, and reluctance of the testing personnel the team decided not to pursue a live firing of the vehicle prior to the conclusion of the current team's schedule. This did not have a significant impact on the concept demonstration, since the main purpose of the HGV was to test the accelerations of launch, which was accomplished with the canister test. An unknown factor in the success of the design remains the proper functioning of the deployment system, which could be determined with further testing.

6.8 Projected Performance

Throughout the project the performance of the Operational Vehicle was predicted based on the design of the HGV. Data for gun elevation, launch accelerations, ballistic flight speed, and drag of the launch and flight support system was included in the analysis. Deployment timing was estimated, and together with the vertical speed and altitude, a minimum deployment altitude was determined to be 3,000 feet. A maximum altitude for successful engine start was estimated to be

7,500 feet. Within this window, the deployment sequence had to occur, and the flyer begin its mission with sufficient altitude remaining. Engine performance combined with the fuel volume indicated twelve minutes of powered flight was possible. Following engine shut down, and depending on the altitude, the flyer could glide for about five minutes. This data was plotted to determine the reconnaissance area based on sensor resolution, gun elevation, altitude at deployment, and ballistic range. A three dimensional plot shown in Figure 6.11 was used to compare the size of the possible reconnaissance areas.

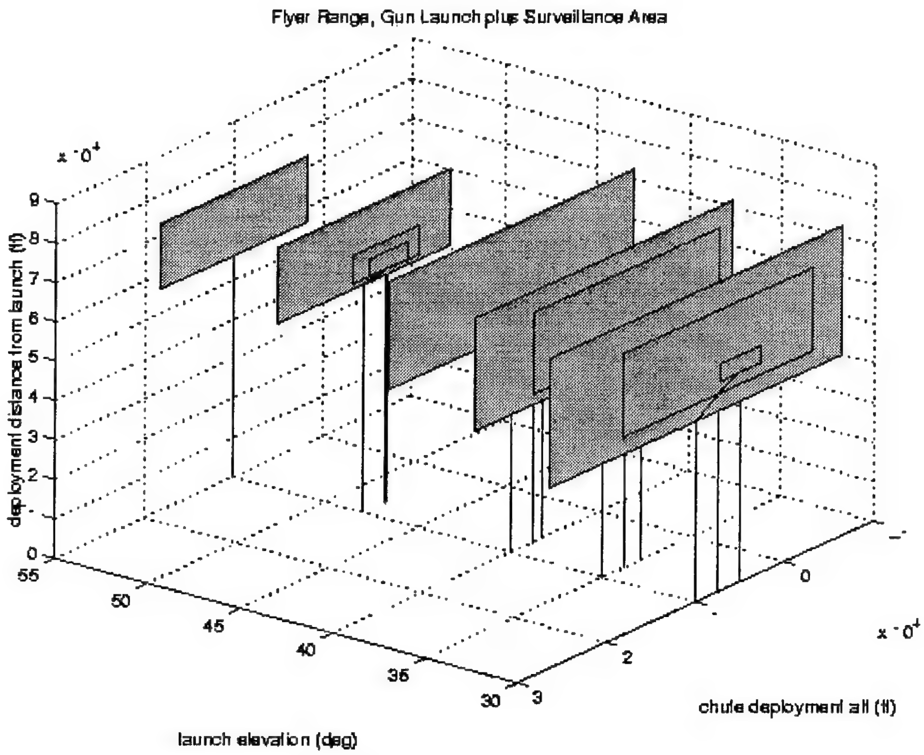


Figure 6.11: Projected Reconnaissance Area as a Function of Range, Launch Elevation, and Deployment Altitude

This plot was further divided into simpler plots for each gun elevation. Since the ability to perform reconnaissance at a range similar to current artillery rounds is important, a flight profile was created where the flyer would deploy at the best possible range, fly straight to reach the maximum artillery range of fifteen nautical miles, and then begin the search pattern. These areas were plotted and compared, and demonstrated a slight reduction in area after using fuel to reach the necessary range. Another profile for straight flight was added to determine the absolute maximum

range for the vehicle using powered and gliding flight. This data was combined on plots for each gun elevation. A plot for the optimum gun elevation of forty degrees is shown in Figure 6.12. More detailed discussion of these results can be found in [18] and [31].

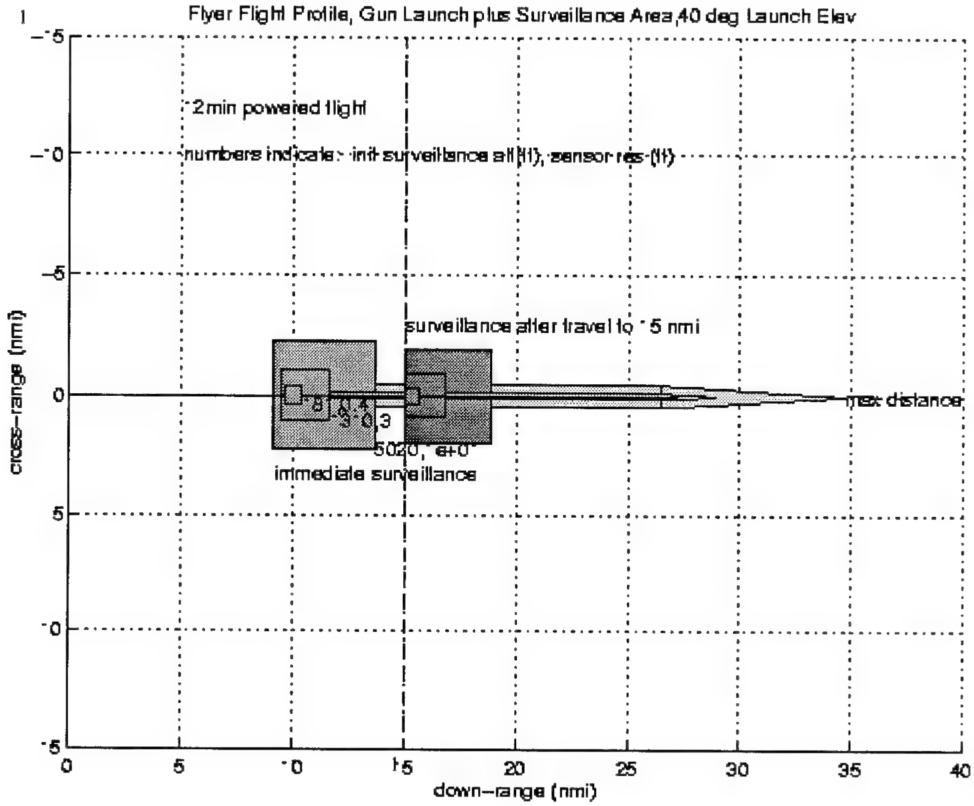


Figure 6.12: Projected Vehicle Performance

7.0 Conclusions and Recommendations

Following sections include suggestions and observations for further work on the design of the WASP vehicle and lessons learned that may prove helpful with similar projects in the future.

Draper Laboratories will receive the work performed by the students to further pursue the product development or spin-off technologies. Draper's capabilities in designing sensors and micromechanical devices and their prior experience with smart munitions will make possible the complete integration and design of the WASP system, allowing them to deliver the technology as a solution to the national need identified in the first year of the project. This will significantly

reduce the time from project end to production for Draper since two years worth of design work will have been performed by the students.

MIT benefited from the program, because it provides an outside source of funding for many graduate students and thesis subjects, and exposed the students to real-world product development, design, and testing. The nature of the project required extensive system engineering issues to be addressed, allowing graduate students valuable and real exposure to this area. The students learned communication skills and gained experience in team design where cooperation and good team dynamics are necessary for success. The success of the project and possible technology spin-offs applied to other research programs demonstrates the ability of MIT students to compete in industry product development, and reflects well upon the education and facilities provided by the Department of Aeronautics and Astronautics.

An unforeseen benefit of a student-focused product development team was the immense amount of assistance received from outside sources. During development of the launch and flight support system the author was able to receive three illumination round projectile bodies and two sets of SAL-GP fins at no cost to the project. Personnel at Dahlgren, Crane, Special Devices, Incorporated, Ensign Bickford, numerous other explosive companies, and other private industry contacts provided assistance and information that improved system development. Picatinny Arsenal supported multiple tests at their airgun facilities. Canister testing at Dahlgren occurred on the same day as an outside company, reducing the cost by half, and was fully supported by Dahlgren personnel. The team was often able to purchase supplies and equipment at educational prices instead of the premium prices charged to private industry. Student involvement in this project saved thousands of dollars and allowed extensive free consultation with outside experts. Benefits of this arrangement are aptly demonstrated by the success of the project and the high regard industry experts have for the vehicle design.

7.1 Future System Design and Testing

7.1.1 Shell Choice

Design of the next generation illumination round for the Navy is proceeding. It is very similar to the present design except for the aft end, which tapers into a boat tail and reduces the

drag during the ballistic flight by up to twenty-five percent [14]. An exposed cavity in the aft end also decreases drag in the few seconds following launch. A reduction in wall thickness at the shell base from the boat tail required a quarter inch decrease in inner diameter. These changes result in less cargo volume but increased range.

This new design is currently being qualified by the Navy for use and replacement of the current shell. These design changes to the shell could increase the WASP vehicle's ballistic range, an important performance measure for WASP. The new shell is likely to replace the old design, which may make acquisition of old projectile bodies more difficult. On the other hand, producing WASP could provide a way to use the old projectile bodies. If a similar project were to be pursued in the near future, this shell could be chosen over the older design. The reduction in wall diameter would not be a problem if the current trend in reducing the size of electronic components continues.

7.1.2 Integration with Existing Navy Guns and Gun Mounts

In order to become fleet qualified, the current design must be compatible with the automatic gun mounts used today. A definitive answer to this question was not determined for the current design, due to increase in length of the overall vehicle compared to current shells. Testing in an actual gun auto-loading system would confirm whether the vehicle interfaced correctly. Determining actual performance during launch would require the launch of a vehicle with identical exterior design and weight distribution. Prior to a real gun launch of a fully functional vehicle, obturator placement and function should be tested to ensure that increasing shell length does not affect performance.

7.1.3 Stabilization

If length is a problem, removal of the fins in favor of spin stabilization may be possible. Careful placement of components within the flyer would be necessary, but would significantly reduce the complexity of the base design. Existing shell obturators could be used, reducing the need for removal and assembly of a new obturator. Spinning would require a point in the deployment process where the flyer is de-spun, perhaps during deceleration or by the control surfaces themselves. The electronics within the flyer would also have to operate without being affected by

spinning. A trade study determining which approach would be more advantageous should occur at a point in the design process when these questions can be answered.

7.2 Lessons Learned

The following suggestions relate less to the design of the flyer than to the organization and operation of the graduate student design teams assigned to similar projects. They are aimed at using the author's experience in the MIT/ Draper Technology Development Project to improve the operation and performance of future graduate student teams.

7.2.1 Design Flow and Communication

The author suggests that a team folder or some sort of data log be kept that includes copies of all important papers or decisions and is accessible to the entire team. Useful documents such as old presentation slides should also be kept in a location known and available to everyone. Poor communication was not a recurring problem but did occur. Occasionally design choices and work was performed with inadequate information or with data that had recently changed, but none of these instances led to extensive rework. Many of these problems were eased by the use of a single directory on one workstation that contained all of the design models, from which detailed information was available. This directory often became cluttered but was a very useful tool in updating system design and granting access to all users.

Often effective communication did not occur between the students prior to the weekly meetings. Important or controversial decisions should be reviewed by the students prior to official meetings so that all members are prepared. Generally when prior communication occurred the students were able to explain the decision and satisfy inquiries more efficiently. A short weekly meeting of just the students occurring just before the official meeting or even a day or two prior may have improved the honest, straightforward communication within the team, avoided team member conflict during meetings, and reassured the meeting participants of successful ongoing system design.

7.2.2 Scheduling

The Draper Project was often beset with scheduling problems, resulting in the repeated delay and rescheduling of tasks, that almost jeopardized completion of the project. The author learned that some of his own delays resulted from inaccurate time estimates for completing work. Waiting for important communication or hardware from outside contacts, not scheduling for academic loads, computer or hardware failure, and not anticipating the complexity of work correctly were the primary reasons for the delays. A solution is likely not in the method or operation of scheduling but rather in the creation. Individuals who set their own personal schedule that feeds into the larger schedule should be careful in estimating time and anticipating possible delays. Often tasks are more complicated and take longer than anticipated. Combining estimate error from all team members can lead to overall project delays and risk successful completion.

7.2.3 Team Structure

Improvement of the scheduling and formation of the Draper Project teams could assist the project and avoid inefficient use of the time available in a two year project. The author believes that every team member incoming for the second year should be required to join the design team in the first summer, soon after the first team completes their work. This allows for every team member to come up to speed on the project at the same pace, and work to be evenly divided from the start of the intensive design process. Team members may begin the required academic course work earlier, reducing the work load during the traditional academic terms resulting in more consistent work over the entire year. The incorporation of some team members in the summer and more a few months later is disruptive and limits the ability of the late team members to become involved in their area of interest. Two year team members should also attempt to limit time away from the project during the summer between the two years, although this would be difficult with many pursuing professional internships.

The use of a student program manager is useful and should be continued. The systems engineering aspect of the position is a valuable education, gives a more consistent overall integration to the design of the vehicle, and can provide team members with useful tools to ease the design choices and base them on relevant, reliable data. The student manager would be more effective throughout the project effort if that person was the same for both years. The team mem-

ber would pursue a Masters of Science or a two year Masters of Engineering. The author believes this would help to ease the transition from the first year to the second year and provide a more complete picture of the project's progression from a student point of view. These two changes outlined above could result in a smoother transition process, a more complete view of the project goals and process flow, and more time spent accomplishing project goals instead of integrating new team structures.

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Appendix A -Test Vehicle Requirements at Start of Second Year

Josh Bernstein

Test Vehicle Requirements
Version 1.0

1. High-g Test Vehicle (HGTV)

1.1 Purpose

The purpose of the HGTV shall be to validate the structural design of the WASP vehicle. It does not, initially, need to demonstrate other functionality of the vehicle (computer systems, sensors, communications, etc.), but should accurately reflect the structural design and layout of the operational vehicle. This vehicle, should, however, be able to be modified to an operational configuration if components become available to facilitate such an upgrade.

1.2 Structure

As a vehicle intended for high-g tests, the HGTV must be able to withstand g-loads representative of those encountered by an operational WASP vehicle. All structures, therefore, must be designed to withstand these loads. Thus both the external shell of the vehicle as well as any and all internal support structures and surfaces (wings, tails, mounting points, etc.) must be designed to these loads.

In addition, for any component not included in the HGTV (see below), "placeholder" weights must be included. These weights should accurately represent the weight, density, and shapes of the components they are replacing.

1.3 Aerodynamic Configuration, Systems, and Deployment

Although intended for high-g testing only, the HGTV must incorporate any and all aerodynamic surfaces that will be used on the operational vehicle (wings, tail surfaces, propeller). These surfaces must be mounted as they would be on the operational vehicle. It is not required for flight control actuators to be included in the HGTV, but placeholder weights must be used (see section 1.2).

Although the deployment system for the flight surfaces does not need to be incorporated into the HGTV, all surfaces must be able to be manually deployed to confirm functionality after high-g testing. If possible, every effort should be made to include the operational deployment systems on the HGTV.

1.4 Propulsion Systems

Since the propulsion system will be subjected to its own series of high-g tests, it does not need to be included in the HGTV. If the propulsion system has passed its high-g tests, however, every effort should be made to include the propulsion system in the HGTV. If the propulsion system is not included in the HGTV, placeholder weights must be used in its place (see section 1.2).

1.5 Autonomy/Flight Control Systems

No computer systems related to autonomy aspects of WASP need to be included in the HGTV. Placeholder weights must be used to represent these components, however, and the vehicle should be capable of being modified to accommodate these systems in the future.

1.6 Communications

There is no need to include communications systems on the HGTV beyond systems used for data collection about the high-g tests. The HGTV should, however, be manufactured to allow for such systems to be incorporated at a later date.

1.7 Sensor Systems

No sensor systems need to be incorporated into the HGTV. Placeholder weights must be used, however, and the HGTV should be capable of being modified to accommodate sensor system components in the future.

1.8 Self-Destruct Mechanism

No self-destruct mechanism needs to be incorporated into the HGTV. Placeholder weights must be used, however, and the HGTV should be capable of being modified to accommodate the self-destruct mechanism in the future.

1.9 Ground Station

No ground station or related systems need to be developed for the HGTV.

2. Air Drop Test Flyer (ADTV)

2.1 Purpose

The purpose of the ADTV is to demonstrate the aerodynamic configuration of the operational WASP vehicle. Since validation of the aerodynamic configuration is the vehicle's primary mission, every effort must be made to ensure that the vehicle accurately represents the operational aerodynamic configuration of WASP. While the vehicle's structure should be designed for the high-g environment, its components need not be. In addition, while it is desired that the ADTV demonstrate some of the functionality of the operational system (autonomy, sensors, communications, etc.), such functionality can be sacrificed to achieve a configuration which exactly represents that of the operational vehicle. The vehicle should be capable of being modified to include the components needed to achieve full system functionality if they become available in the future.

2.2 Structure

The ADTV's internal structure and external shell should be designed to the high-g environment of the operational vehicle. In this regard, the ADTV and the HGTV should be identical. However, no internal components of the ADTV (electronics, engine, etc.), need

to be capable of withstanding these loads. In addition, since the ADTV is to serve as an aerodynamic model of WASP, all components should be distributed to achieve the proper weight and balance of the operational vehicle. If needed, additional weights should be placed in the vehicle to achieve this distribution.

2.3 Aerodynamic Configuration, Systems, and Deployment

As stated in section 2.1, the ADTV must be an exact representation of the operational vehicle in terms of its aerodynamic configuration. In addition, all flight control surfaces must be operational, and the vehicle must demonstrate that it is controllable, either via on-board electronics or by remote control (see section 2.5 below).

The ADTV should also be capable of demonstrating the deployment of all flight control surfaces, as well as other deployable structures. The deployment mechanisms must be at least demonstrated in testing on the ground, and should also be demonstrated in flight (i.e., vehicle released in stowed configuration, then transforms into deployed configuration).

2.4 Propulsion Systems

The ADTV must have an operational propulsion system. This system should be an accurate reflection of the system that will be used on the operational WASP vehicle. The ADTV does not, however, need to demonstrate the complete loiter time or range of the operational vehicle if space that would be used for fuel is devoted to other equipment. If a complete fuel load is carried by the ADTV, however, it should be capable of demonstrating the operational mission performance.

2.5 Autonomy/Flight Control Systems

Systems related to vehicle autonomy and flight control must at least include those systems required to ensure that the vehicle is stable in flight (if such systems are required). Any additional systems related to vehicle autonomy can be included at the design team's discretion. The only restriction is that the vehicle must always conform to the operational vehicle's aerodynamic configuration. If the inclusion of autonomy-related systems would jeopardize this requirement, the systems will not be included. Any autonomy related systems that are included in the design, however, do not need to be g-hardened.

In the event that the vehicle can not accommodate autonomy related systems, the ADTV should be designed to operate as a remotely piloted vehicle. All components for such operation should then be included in the vehicle, and appropriate weights added to ensure that the vehicle still conforms to operational vehicle's weight distribution.

2.6 Communications

Any communications systems included in the ADTV should match the needs of the vehicle. In the event that the vehicle includes autonomy related systems, the communications system should be capable of relaying basic telemetry about the vehicle's state (position, attitude, altitude, velocity). If a sensor is included in the ADTV, the communications system should be capable to relaying imagery to the ground. In addition, if an operational ground station has been developed, the communications system should be capable of handling transmissions between the ADTV and the ground station. (See section 2.5 above and sections 2.7 and 2.9 below).

2.7 Sensor Systems

A sensor should be included in the ADTV. The purpose of the inclusion of the sensor is to gain some data regarding image quality from an operational WASP vehicle. This sensor does not need to be g-hardened, but should allow for transmission of imagery to the ground.

2.8 Self-Destruct Mechanism

No self-destruct mechanism needs to be included in the ADTV. However, the vehicle should be capable of being modified to include such a mechanism in the future.

2.9 Ground Station

Every effort must be made to prepare some degree of functionality in a ground station for the ADTV. This functionality is dependent upon other factors in the ADTV design:

- If the ADTV is remotely piloted, the ground station must incorporate the user controls to facilitate remote operation of the vehicle.
- If a sensor is incorporated into the ADTV, the ground station must be capable of displaying images sent back from the flyer.
- If autonomous systems are included in the ADTV, the ground station must do one of the following:
    - If two way communications are available, the ground station should be capable of sending commands to the ADTV's computer.
    - If two way communications are not available, ground station commands (i.e., a command stack) should be downloaded into the ADTV prior to its flight so that the vehicle can operate as though it was receiving a series of commands from the ground.

No matter what systems are eventually incorporated into the ADTV, the ground station must be capable of receiving and displaying any telemetry sent by the ADTV.

3. Note on ADTV/HGTV Commonality

Since both vehicles are to include structures that can withstand the high-g environment of the operational vehicle, the possibility does exist for the functions required of the two vehicles to be incorporated into a single vehicle. If such an option were to be pursued, a mechanism would have to be included in the design to facilitate the addition/removal of systems to be used in the drop tests but not the g-tests after/before such tests were conducted. It would be up to the discretion of the team to determine which vehicle configuration to construct first, depending on test plans.

Appendix B -Component Lists for the Flight Test Vehicle (referred to as Air Drop) and the Operational Vehicle

Operational Vehicle Component List

Definitions: x-axis: longitudinal axis of the flyer through the nose
y-axis: out right wing of the flyer
z-axis: through bottom of the flyer

Known Components

Component Name		Manufacturer	Cost	Number	Dimensions (cm) x-axis	y-axis	z-axis	Volume (cm3)	Mass (g)	Current Draw (Amps)	Voltage (Volts)		Reference
GPS Receiver													
IMU	Current	Draper	N/A	1	8.636	Cylinder d=	6.858	319.004721	680.4	11 W	15	;+-5	
CPU													
GPS Antenna	Projected	Draper	N/A	1	5	5	5	125					Draper/ Vlad
Power Board	2-3 years	Tom Marinis											
Telemetry													
Casing													
D/A Converter													
Servo Rods			$ 3.00	2	5	rod d= 4	0.2	0.314159	15				Torrey
Servos (3)		Futaba	$ 90.00	3	2	4	3.6	86.4	50				Vlad
Wings		Torrey/ Thierry	$ 1,500.00	1	13	10	5.5	715	500				Thierry
Tail Surfaces		Thierry/ Torrey	$ 200.00	2	15	7	1	210	200				Torrey/ Thierry
Propeller		MIT	$ 500.00	1	1.905	4.48	1.905	16.258032					Ted
Engine		OS Engines .15	$ 60.00	1	4.445	3.81	6.826	115.601382	200	0.125	1.5		Ted
?Starter		Ted		1	12.7	cyl d=	3.81	144.79154	500				Ted
?Fuel Tank		MIT	$ 40.00	1	6.634	10.16	10.16	684.79863	1400				Ted
Battery	Actual	Eagle&Prichter	$ 3,500.00	??	5	cyl d=	5	98.1746875	26				Draper (ATD)
	Projected	same	???		energy density--> volume required								
	2 years												
Totals			$ 5,893.00						3571.4				

Unknown Components

Component Name		Responsibility	Cost	Number	x-axis	y-axis	z-axis	Volume	Mass	Current Draw	Voltage		Reference
Slow-down Mechanism		?????			?	?	?	?					
Camera		estimated		1	6	2	8	96					Bernard
Power Distrib		estimated		1	6	2	6	72					Bernard
Modem/ Transceiver		Vlad + ..							37.5 %Structu	Total			
						Actual Current Volume =		2558.34315	959.378682	3517.721833			
						Projected Volume =		2364.33843	886.626911	3250.965342			

ADTV Component List

Definitions:
x-axis: longitudinal axis of the flyer through the nose
y-axis: out right wing of the flyer
z-axis: through bottom of the flyer

Known Components

Component Name	Manufacturer	Cost	Dimensions (cm) x-axis	y-axis	z-axis	Mass (grams)	Current Draw (Amps)	Voltage (Volts)		Reference
GPS Receiver	Ashtech	$ 4,000	5.842	1.27	10.92	55.07	1.4 W	5		Vlad
IMU	Systron Donner	$ 13,000	8.89	7.62	7.62	907.2	0.259	15	-15	Vlad
CPU	Ampro/ 3M	$ 500	9	9.6	2	92	0.93	5		Vlad
Ethernet	Ampro	$ 200					1-2 W	5		Vlad
Mini-Module Serial Ports	Ampro	$ 200					1-2 W	5		Vlad
A/D Converter	Win Systems	$ 200	above 3 components make up dimensions of CPU				0.03	5	-12	Vlad
UHF Transmitter		$ 1,500	7.62	7.62	2.54	113.4	0.16	12		Vlad
Modem	Motorola	$ 1,000	8.382	6.858	3.861	311.84	4 W	?		Padraig
D/A Converter (FPGA)	Draper		5.08	3.81	6.35	100	0	0		Padraig
RC Receiver	Futaba		5.55	2.55	2.25	30.4	0.014	4.8		Vlad
Servos (3)	Futaba		2.01	4.04	3.6	48.2	0	0(4.8)		Vlad
GPS Antenna	Ahtech		8.74	5.59	1.55	110.6	0	0		Vlad
Engine	OS Engines .15	$ 60	4.445	3.81	6.826	200	0.125	1.5		Ted
Engine Starter	MIT (FEMA?)	$ 200	6.35	6.2	6.2	400	?	?		Ted
Fuel Tank	MIT	$ 40	6.634	10.16	10.16	1400				Ted
Power Board (Regs)	MIT		7.62	7.62	1.27	400				Ted
Batteries (+backup) (5 or 6)	Varta	$ 60	6.68	1.7	1.7	52	3.5	1.2		Ted
Propellor	MIT	$ 500	1.905	4.48	1.905	?				Ted
Propellor Mount	MIT		1.27	2.54	1.27	?				Ted
Nose Cone	MIT		2.54	2.54	2.54	?				Ted
Servo Rods (3)	Torrey/ Thierry	$ 1.00	5	0.508						Torrey
Camera		$ 200.00	3.81	3.81	2.54	28.35	0.1	12		Vlad/ Padraig
TOTALS		$ 21,661				4249.06	5.118			

Unknown Components

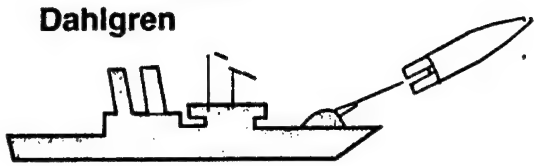
Component Name	Responsibility	
Retrieval chute	Sebastian	
R. Chute Mechanism	Sebastian	
Telemetry	??? [Vlad/ Ted/ Torrey]	Telemetry = wires, tachometer (1), Potentiometers (2), pre-filters

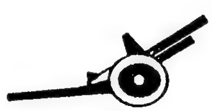
Appendix C -Detailed Operational Sequence, Versions 1 and 2

WASP Operational Timeline

Launch

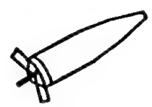
Time t = 0 s
Speed v = Mach 2 ?
Altitude h = 0 ft
Running R: TCXO
Trigger Tr: Launch
Test Ts: Final
Dahlgren





Fin Deployment

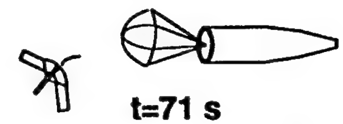
t = 2 s
v= Mach 2
h= 100 ft?
R: TCXO
Tr: Barrel Exit
Ts: Final Dahlgren



Back End Separation

t= 69 s
v= Mach 1
h= 8000 ft
R: GPS CPU
IMU modem
Tr: CPU timer
Ts: Static Sep
Drop Test

Parachute Inflation



t=71 s
v= < Mach 1
h= 7750 ft
R: same
Tr: Parachute in
airflow
Ts: Drop Test

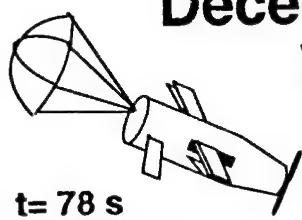
Prior to Launch

External Power Up
Program
External Power Disconnect
TCXO Internal Power Connect
Turn on TCXO

Flyer Separation

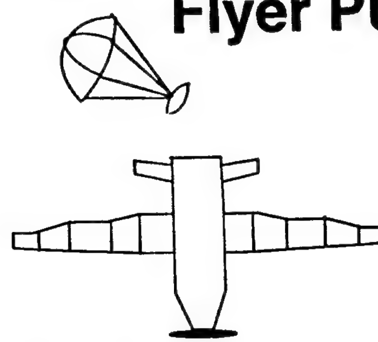
t= 71+ s
v= 1100 ft/s
h= 7500 ft
R: same
Tr: Parachute Force
Ts: Drop Test

Decelerated/ Wing Pivoted



t= 78 s
v= 250 ft/s
h= 5000 ft
R: same, servos engine start
Tr: prop spring
Ts: Drop Test?? Static Wind Tunnel Test

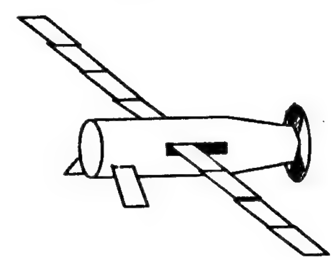
Wing Unfolded/ Flyer Pull-up



t= 81 s
v= 250 ft/s
h= 4500 ft
R: all
Tr: CPU -> explosive bolt
Ts: Drop Test? Final Dahlgren? Static?

Mission

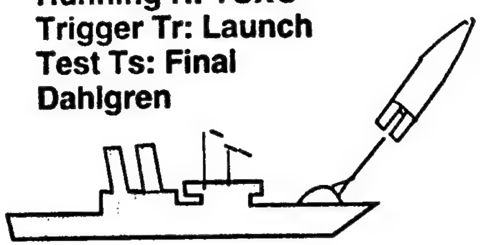
t= 84 s -> mission end
v= 150 ft/s
h= 3000 ft
R: all
Tr: Tails level out
Ts: Air Drop Vehicle

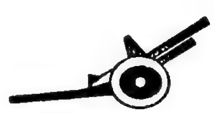


WASP Operational Timeline

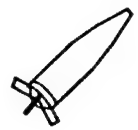
Launch

Time t = 0 s
Speed v = Mach 2 ?
Altitude h = 0 ft
Running R: TCXO
Trigger Tr: Launch
Test Ts: Final
Dahlgren



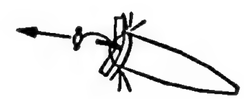


Fin Deployment



t = 2 s
v= Mach 2
h= 100 ft?
R: TCXO
Tr: Barrel Exit
Ts: Final Dahlgren

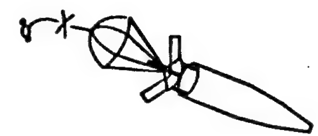
Back End Separation /Cover Release



t= 69 s
v= Mach 1
h= 8000 ft
R: GPS CPU
IMU modem
Tr: CPU timer
Ts: Static Sep
Drop Test

Parachute Inflation/ Flyer Extraction

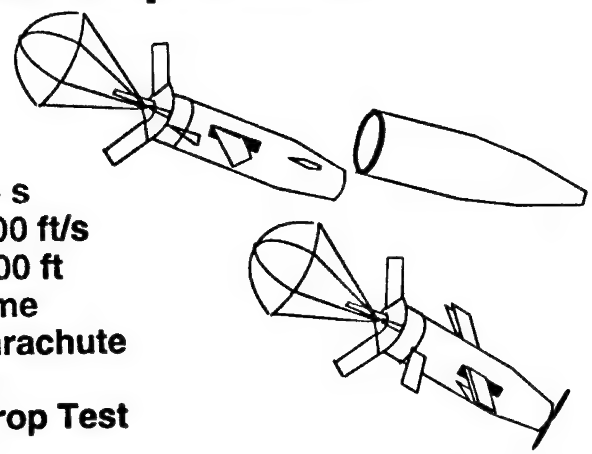
t=71 s
v= < Mach 1
h= 7750 ft
R: same
Tr: Parachute in airflow
Ts: Drop Test



Prior to Launch

External Power Up
Program
External Power Disconnect
TCXO Internal Power Connect
Turn on TCXO

Flyer Separation

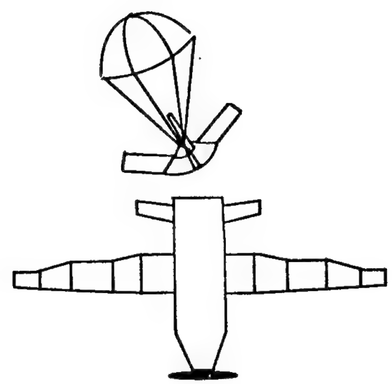


t= 71+ s
v= 1100 ft/s
h= 7500 ft
R: same
Tr: Parachute Force
Ts: Drop Test

Decelerated/ Wing Pivoted

t= 78 s
v= 250 ft/s
h= 5000 ft
R: same, servos engine start
Tr: prop spring
Ts: Drop Test?? Static Wind Tunnel Test

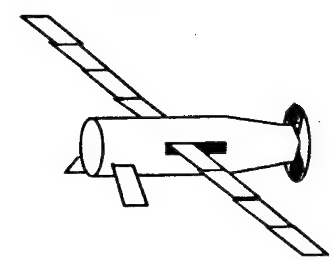
Wing Unfolded/ Flyer Pull-up



t= 81 s
v= 250 ft/s
h= 4500 ft
R: all
Tr: CPU -> explosive bolt
Ts: Drop Test?
Final Dahlgren?
Static?

Mission

t= 84 s -> mission end
v= 150 ft/s
h= 3000 ft
R: all
Tr: Tails level out
Ts: Air Drop Vehicle



Appendix D -Engineering Drawings for the Mark 48 Mod 1 Illumination Projectile Body and Base Plug

CLASSIFICATION OF CHARACTERISTICS	
CRITICAL- NONE	MAJOR- 18
MINOR- DOD-STD-2101	

REVISIONS				
ZONE	LTR	DESCRIPTION	DATE	APPROVED
	C	(1-13) SEE NOR 1381171-C. REPLACES REV B WITH CHANGE.	76-10-27	DHS DTJL
	D	(1-5) SEE NOR 1381171-D	80/4/19	

NOTES: (C2) (D2)

1. INTERPRET DRAWING IN ACCORDANCE WITH DOD-STD-100.
2. UNLESS OTHERWISE SPECIFIED:
   - 250/ ALL OVER.
   - REMOVE BURRS AND BREAK SHARP EDGES .010 MAX.
   - ALL DIMENSIONS APPLY BEFORE GRADE A SURFACE PROTECTION.

(M101) 3. BODY ASSEMBLY WEIGHT SHALL BE 42.11 POUNDS ± .45 POUNDS (BODY 40.16 POUNDS NOMINAL AND BANDS 1.95 POUNDS NOMINAL). CORRECT WEIGHT IS NOT DIMENSIONALLY ASSURED. CONTROL DIMENSIONAL VALUES AND MATERIAL DENSITY TO HOLD WEIGHT WITHIN TOLERANCE.

4. THE REQUIREMENTS OF MIL-P-18950, AS SUPPLEMENTED BY MIL-P-18949, APPLY.
5. GRADE A SURFACE PROTECTION IS REQUIRED IN ACCORDANCE WITH MIL-P-18948, EXCEPT THAT ALL THREADS SHALL BE COATED WITH SILICONE COMPOUND, ITEM 3.
   5.1 THE BOURRELET DIAMETERS SHALL NOT EXCEED 4.986 AFTER GRADE A SURFACE PROTECTION.
6. THE REQUIREMENTS OF WS-15061 APPLY.
7. MATERIAL SHALL BE STEEL, AISI 1050 PER FED-STD-66, EXCEPT THAT MANGANESE CONTENT SHALL BE 1.35 TO 1.60 PERCENT.

(M120) 7.1 MECHANICAL PROPERTIES:
   - TENSILE STRENGTH: 105,000 PSI MIN
   - YIELD STRENGTH AT .01% OFFSET: 78,000 PSI MIN
   - ELONGATION: 18% MIN
   - REDUCTION IN AREA: 35% MIN

8. PACKAGING OF THE BODY ASSEMBLY SHALL BE IN ACCORDANCE WITH DRAWING 2838392.
9. FOR LIST OF APPLICABLE DOCUMENTS SEE DL1381171.

(M103) 10. BODY ASSEMBLIES SHALL BE SELECTED AND MATCHED WITH MATING BASE PLUG, PART NUMBER 2838596, 2838998 OR 5356552, FSCM 53711, AS APPLICABLE TO ENSURE AN INTERFERENCE FIT OF .004 ± .001 ON THE 3.97 DIAMETER.

   10.1 THE BODY SHALL BE STEEL STAMPED ON THE FORWARD BAND TO PROVIDE IDENTITY OF MATING BODY ASSEMBLY AND PLUG. CHARACTERS SHALL BE 3/16 HIGH.

11. MARKING IDENTIFICATION SHALL BE STEEL STAMPED IN 3/16 HIGH CHARACTERS ON FWD ROTATING BAND CONSISTING OF THE CODE IDENTIFICATION NUMBER, DRAWING NUMBER AND APPLICABLE REVISION LETTER (EXAMPLE: 10001-1381171-C).
12. ENGINEERING DATA SUMMARY; DC 52479 (FOR NSWC/DAHLGREN AND NAVSEASYSCOMHQ (SEA-9926) USE ONLY).
13. AMERICAN NATIONAL, CLASS 2 FORM THREADS, ARE ACCEPTABLE FOR ANY THREAD SIZE.

(D1) (C7)

REVISION STATUS OF SHEETS		
SHEET 1	C	D
SHEET 2	C	D
SHEET 3	C	D

1381171

(C3)

ITEM NO	QTY REQ	CODE IDENT NO.	PART OR IDENTIFYING NO.	SPECIFICATION NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL OR NOTE
3	AR			MIL-C-21567	COMPOUND, SILICONE	NOTE 5
2	2		-2	MIL-B-18907	BAND, PROJECTILE ROTATING	GILDING METAL
1	1		-1		BODY	NOTE 7 & 7.1

PARTS LIST

NEXT ASSY	USED ON
	PJCTL, 5"/54 CAL, LOAD EXPELLING ASSEMBLIES

APPLICATION

(C4)

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES
TOLERANCES (C6)
ANGLES ± 5°

XX DECIMAL	XXX DECIMAL	FRACTION
±.02	±.010	± ~

DO NOT SCALE THIS DRAWING
MATERIAL: (C5)
SEE PARTS LIST

NAVAL SURFACE WEAPONS CENTER
DAHLGREN LABORATORY
DAHLGREN, VA. 22448

DG 50		76-10-26
DG 50/E		76-10-26
DT 33		76-10-21
DT 32		76-10-20
DT 324		10/14/76
CHECKED	B.L.J.	10/14/76
PREPARED	RHL	76/7/28
APPROVED FOR NAVSEA		76/10/27

DEPARTMENT OF THE NAVY
NAVAL SEA SYSTEMS COMMAND
WASHINGTON, D.C. 20362

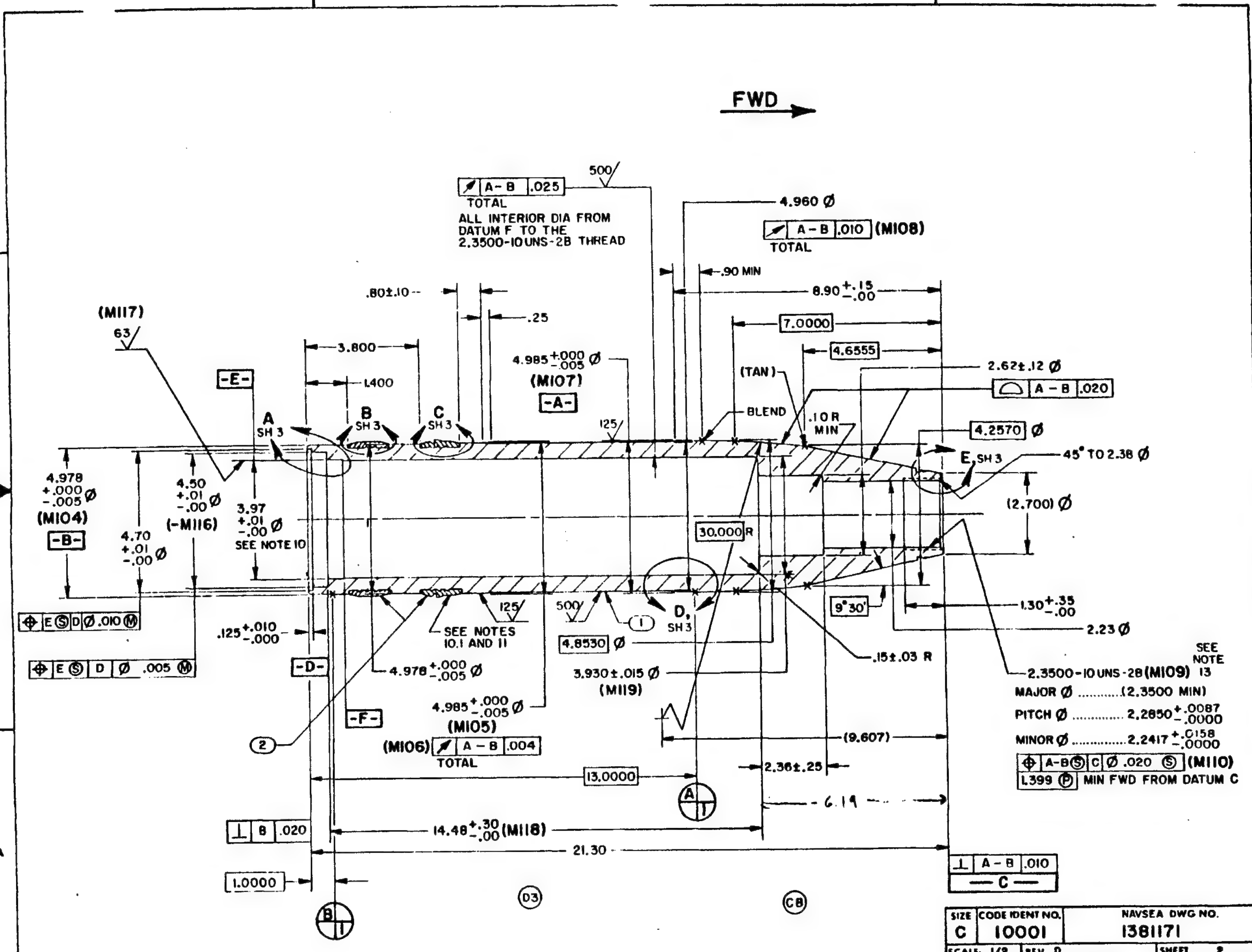
BODY ASSEMBLY, 5 INCH 54 CALIBER, MARK 48 MOD 1

(C1)

SIZE	CODE IDENT NO.	NAVSEA DWG NO.
C	10001	1381171

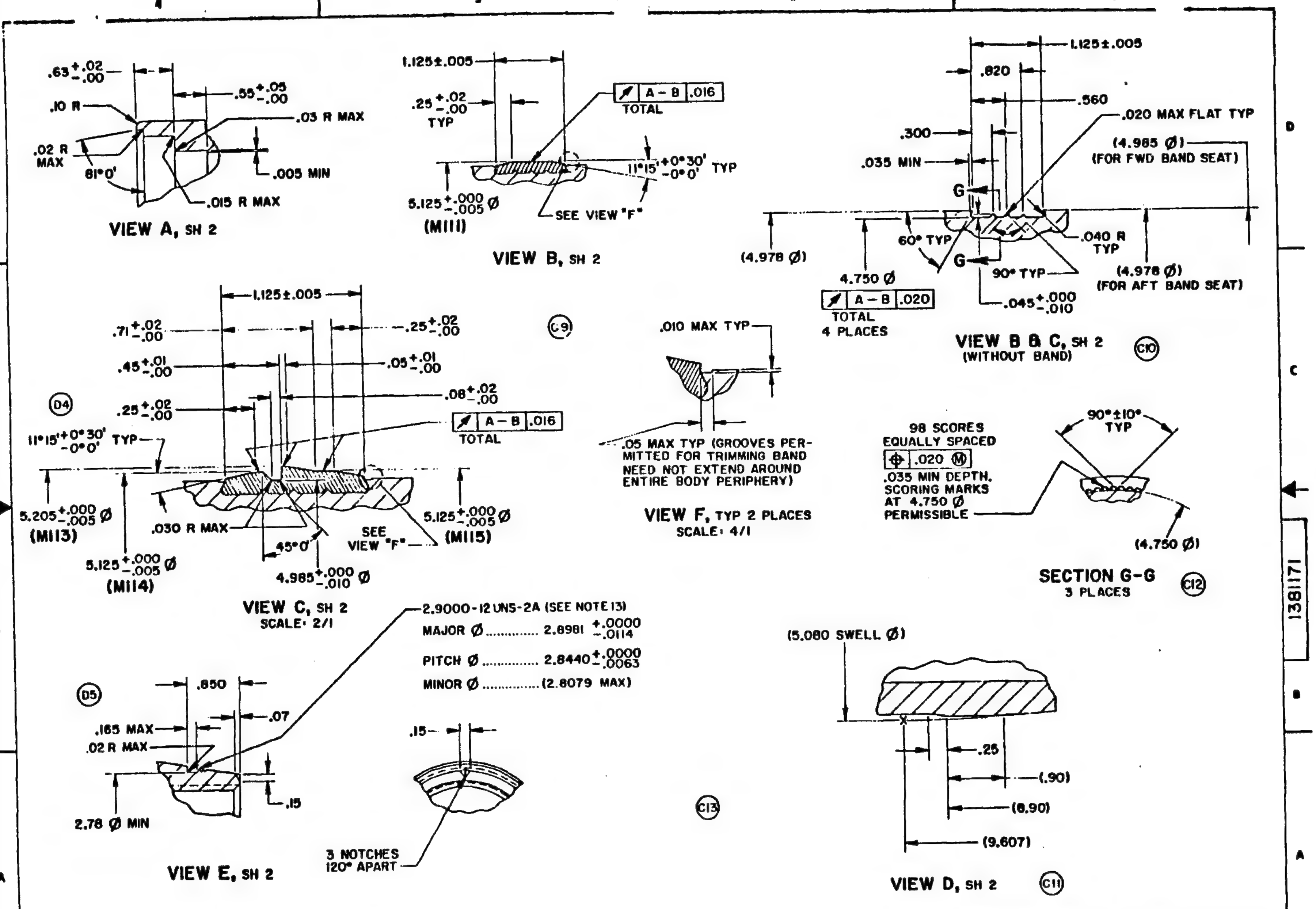
SCALE: NA
SHEET 1 OF 3

NDW-NSWC/DL-5603/3 (REV 1-76)



SIZE	CODE IDENT NO.	NAVSEA DWG NO.
C	10001	1381171
SCALE: 1/2	REV D	SHEET 2

NSW NWL 1002/1A (REV 8/69)



SIZE	CODE IDENT NO.	NAVSEA DWG NO.
C	10001	1381171
SCALE: 1/1	REV D	SHEET 3

NDW-NWL 5602/3A (REV 8/69)

CLASSIFICATION OF CHARACTERISTICS	
CRITICAL- NONE	MAJOR- 3
DOD-STD-2101	

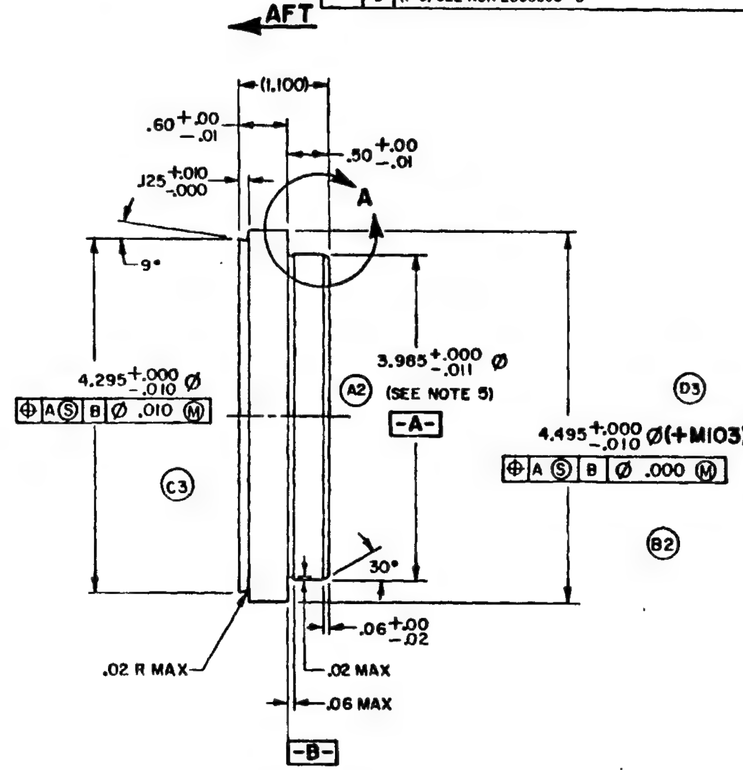
REVISIONS

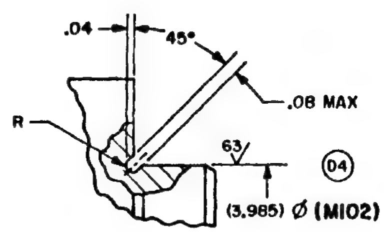
ZONE	LTR	DESCRIPTION	DATE	APPROVED
	A	(1-3) SEE NOR 2838596-A	5-18-72	JRS (EPT)
	B	(1-6) SEE NOR 2838596-B	[illegible]	[illegible]
	C	(1-4) NOR 2838596-C	80/03/12	DHG E32
	D	(1-5) SEE NOR 2838596-D	84/3/15	DHG

NOTES: (A1) (B1) (C2) (D2)

1. INTERPRET DRAWING IN ACCORDANCE WITH DOD-STD-100.
2. UNLESS OTHERWISE SPECIFIED:
   250/ ALL OVER.
   REMOVE BURRS AND BREAK SHARP EDGES .010 MAX.
   ALL DIMENSIONS APPLY BEFORE GRADE A SURFACE PROTECTION.
3. GRADE A SURFACE PROTECTION IS REQUIRED IN ACCORDANCE WITH MIL-P-18948 ON ALL SURFACES EXCEPT DATUM B AND THE 3.985 DIA.
4. MATERIAL SHALL BE STEEL, AISI 1050 PER FED-STD-66, EXCEPT THAT MANGANESE CONTENT SHALL BE .95 TO 1.30 PERCENT.
   4.1 THE BASE PLUG SHALL CONFORM TO THE FOLLOWING MECHANICAL PROPERTIES WHEN TESTED IN ACCORDANCE WITH FED-STD-151 METHOD ASTM E8, ROUND TEST SPECIMEN:
   TENSILE STRENGTH - - - - - - - - - - - - 105,000 PSI MIN
   YIELD STRENGTH AT .01% OFFSET - - - - - 78,000 PSI MIN
   ELONGATION - - - - - - - - - - - - - - - - - - - 18% MIN
   REDUCTION IN AREA - - - - - - - - - - - - - - 35% MIN

(M101) 5. BASE PLUGS SHALL BE SELECTED AND MATCHED WITH MATING BODY ASSEMBLIES, PART NUMBER 1381171 OR 2838595-1 TO ENSURE AN INTERFERENCE FIT OF .004 ± .001 ON THE 3.985 DIAMETER.
   5.1 BASE PLUG SHALL BE STEEL STAMPED ON AFT SURFACE TO PROVIDE IDENTITY OF MATING PLUG AND BODY ASSEMBLY. CHARACTERS SHALL BE 3/16 HIGH.
6. PACKAGING OF BASE PLUG SHALL BE IN ACCORDANCE WITH DRAWING 2838392.
7. CALCULATED WEIGHT (4.35 ± .05LBS)





VIEW "A"
ALTERNATE METHOD
SCALE: 2/1

ITEM NO	QTY REQ	CODE IDENT NO.	PART OR IDENTIFYING NO.	SPECIFICATION NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL OR NOTE

PARTS LIST

APPLICATION

	NEXT ASSY	USED ON
(D5)	2838933	PJCTL, 5"/54 CAL, WP, MK 89 MOD 0
(C4)	2838931	PJCTL, 5"/54 CAL, WP, MK90 MOD 0
(B3)	53711-5366676	PJCTL, 5"/54 CAL, ILLUMINATION MK 88 MOD 2
	2839277	PJCTL, 5"/54 CAL, ILLUMINATION, MK 88 MOD 1

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES
TOLERANCES (B4)
ANGLES ± 1°

XXDECIMAL	XXXDECIMAL	FRACTION
±.02	±.010	±

DO NOT SCALE THIS DRAWING
MATERIAL: (B5)
NOTES 4 AND 4.1

U.S. NAVAL WEAPONS LABORATORY
DAHLGREN, VA. 22448

EPD	[illegible]	2-24-72
EPT	[illegible]	2-14-72
EPT-2	JRS	2-22-72
EPT-4	[illegible]	2-7-72
CHECKED	[illegible]	2-7-72
PREPARED	M.P.J.	1-7-72

APPROVED FOR NAVORD
[signature] 2-24-72

DEPARTMENT OF THE NAVY
NAVAL ORDNANCE SYSTEMS COMMAND
WASHINGTON, D.C. 20360

PLUG, BASE

SIZE	CODE IDENT NO.	NAVORD DWG NO.
C	10001	2838596
SCALE: 1/1	WEIGHT: 4.35 REF	SHEET 1 OF 1

2838596

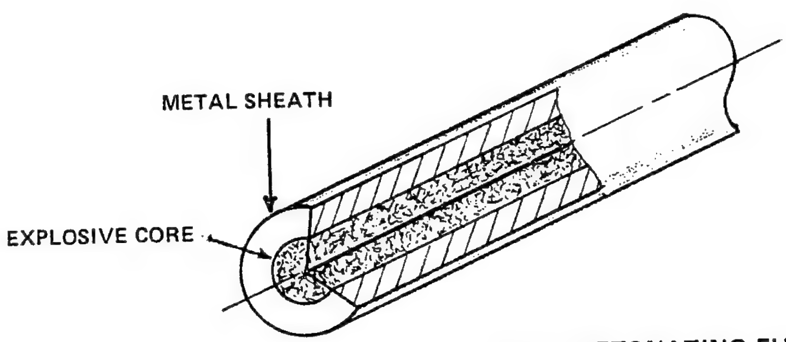
NDW-NWL 5602/3 (REV 8/69)

Appendix E -Explosives Reference Data Applicable to System Design

MILD DETONATING FUSE

1. GENERAL INFORMATION

Mild Detonating Fuse (MDF) is a continuous explosive core encased in a seamless metal sheath. With proper initiation stimulus, the explosive core detonates at a uniform rate as governed by characteristics of the explosive and density of the explosive core.



MILD DETONATING FUSE

Ensign Bickford produces a variety of MDF configurations for applications demanding high reliability in functions such as energy transmission, work, timing and shock effects. High reliability is inherent because of the continuous explosive core and the environmental and structural protection afforded by the seamless metal sheath. MDF is flexible and can be formed to suit individual applications.

Ensign Bickford poineered the development of linear explosive products and, in conjunction with the growth of space technology, developed Low Energy Detonating Cord (LEDC). LEDC, which is now know as Mild Detonating Fuse (MDF), has undergone further development greatly increasing product line and capabilities. With over 25 years of experience in development and production of MDF and associated items, Ensign Bickford offers a complete capability to supply MDF and systems employing MDF to exacting requirements.

Descriptions of MDF construction, applications and types follow. For further information, contact the Aerospace Division, Marketing Department, at our Simsbury, Connecticut facility.

2. CONSTRUCTION AND PERFORMANCE

The explosive material, coreload, sheath material, diameter and detonation velocity of MDF can be tailored to provide specific performance and environmental capability.

Explosives

PETN, RDX and HNS are the most frequently used explosives in Ensign Bickford MDF; large quantities of MDF and Linear Shaped Charge (LSC) have been produced using DiPam, CH-6, PBXN-5, HNAB and HMX. In addition, explosives such as NONA, OCTA, TACOT, DATB and PBXC-12 have been used in production and study programs. Descriptions of PETN, RDX and HNS follow:

PETN, Pentaerythritol Tetranitrate, is an easily initiated secondary high explosive commonly used in linear explosive products. A large use of PETN is in Primacord® detonating fuse. PETN is white in color, has a melting point of 286° F and a detonation rate of 8300 meters per second at a density of 1.7 g/cc. PETN MDF possesses relatively low temperature resistance; 250° F in most applications is the maximum temperature it can withstand for a short time period (under 30 minutes) without degrading. PETN used by Ensign Bickford meets requirements of specification MIL-P-387.

RDX, Cyclotrimethylene Trinitramine. has lower initiation sensitivity and can withstand higher temperature than PETN. It is naturally white in color but is frequently dyed pink for use in linear explosive products. Melting point of RDX is 399° F: the detonation velocity is 8180 meters per second at a density of 1.65 g/cc. Temperature resistance of RDX MDF is dependent on sheath material strength and RDX purity. Most RDX MDF will withstand 300° F or slightly higher for 1/2 hour. RDX used by Ensign Bickford is virgin RDX-type B conforming to specification MIL-R-398.

HNS, Hexanitrostilbene, has lower initiation sensitivity than RDX and PETN and meets the initiation sensitivity criteria of MIL-STD-1316. HNS is pale yellow in color, has a melting point of 601° F and a detonation rate of 6900 meters per second at a density of 1.6 g/cc. Temperature resistance of HNS is excellent, HNS II MDF has satisfactorily performed after 7 days exposure of 460° F. HNS used by Ensign Bickford in MDF is type II conforming to WS 5003 F. Two grades of HNS II are covered by WS 5003. Grade A has been subjected to and passed sensitivity and output tests of WS 5003; grade B has not been subjected to those tests but meets all other requirements of WS 5003. Ensign Bickford produces HNS II with the Organic Process using Acetonitrile Toluene originally developed by Taylor and Oesterling at the Navy Surface Weapons Center White Oak Laboratory.

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Sheath Materials

The most frequently used MDF sheath materials are lead, aluminum and silver; Inconel*, Invar**, stainless steel, copper and other materials have been used for special applications.

Lead Sheathing is 6% antimonial lead conforming to specification MIL-L-18331. Lead sheathed MDF is economical, easily formed and has good flexure capability.

Aluminum Sheathing used in Ensign Bickford MDF is extremely pure and soft. Aluminum sheath MDF contrasted to lead sheath MDF has higher tensile strength, lower weight and retains strength at higher temperatures. Detonation velocity of a given explosive and coreload in aluminum sheath MDF is typically higher than in lead sheath MDF because a higher explosive core density is achieved. Aluminum is more transparent to high energy radiation than lead or silver and; therefore, provides high survivability in such environments.

Silver Sheathing is used most frequently with HNS II explosive. Only high purity silver is used in Ensign Bickford MDF. Silver sheathed MDF has higher strength than aluminum and lead sheathed MDF but is more expensive. Detonation velocity of HNS in silver is higher than that displayed by HNS in aluminum or lead because a higher explosive core density is achieved.

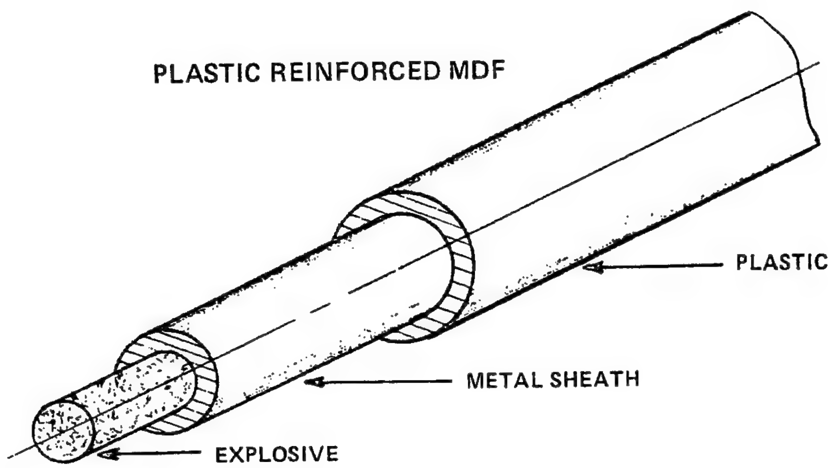
Reinforcing Materials

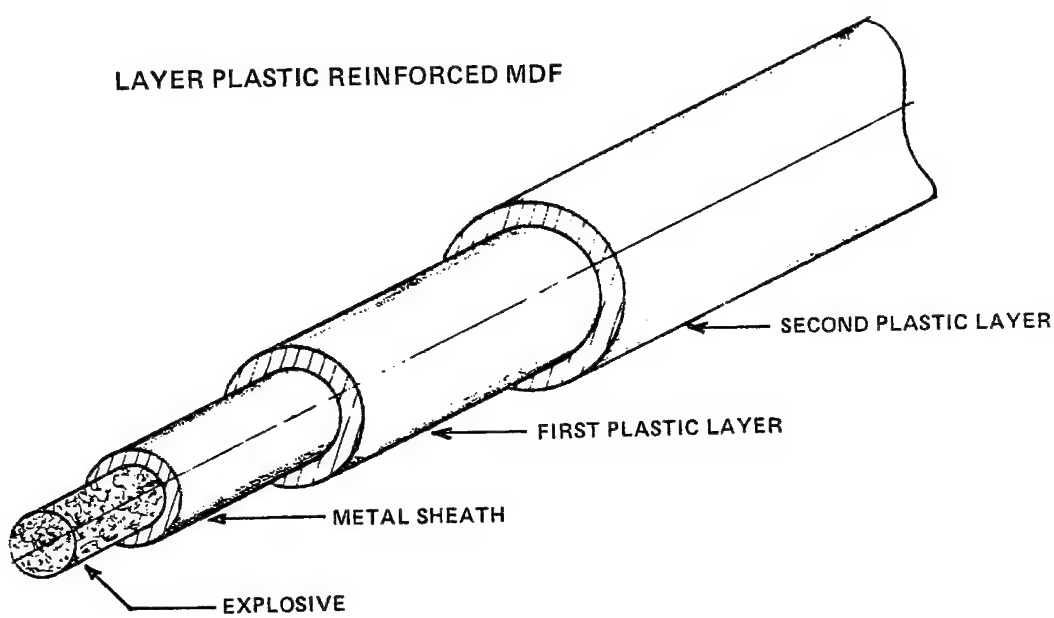
Reinforcing materials are applied to MDF for increased tensile strength, abrasion resistance, vibration and shock protection, and resistance to damage from flexing. Materials applied over MDF vary from plastic jackets to plastic jackets plus high strength woven structures such as fiberglass or Kevlar®. Polyethylene is the most widely used reinforcement; other materials extruded onto MDF include nylon, Teflon®, Kynar®, polyvinylchloride, urethane, foam plastic and vinyl. Extruded multiple layer jackets have been produced such as polyethylene over the MDF and nylon over the polyethylene. Silicone rubber reinforcement has also been used; it is usually extruded separately and the MDF is then inserted into the silicone rubber. Plastics are extruded over the MDF in a controlled process that provides intimate contact with the MDF and close dimensional control. Plastic reinforcement by direct extrusion is superior to heat shrink reinforcement for reasons of lower cost and superior dimensional control.

*T.M. International Nickel Company
**T.M. Driver-Harris Company

®Registered T.M. E. I. DuPont
®Registered T.M. Pennwalt Corporation

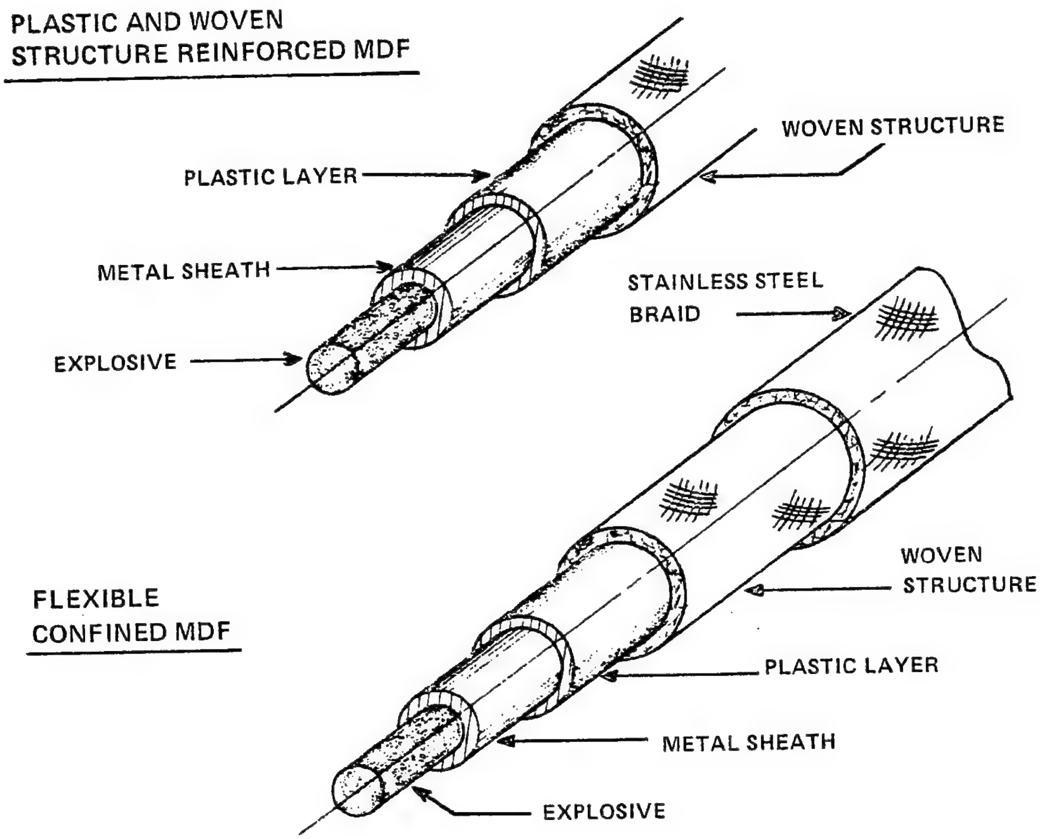
Woven materials applied over plastic reinforced MDF include fiberglass. Kevlar, nylon, rayon, polypropylene and steel wire. Construction of plastic reinforced MDF, layer plastic reinforced MDF and MDF with plastic and woven reinforcement is shown in the following illustrations.





Ensign Bickford company

AEROSPACE DIVISION



Velocity Of Detonation (VOD)

VOD's from 6000 to over 8000 meters per second may be achieved with MDF. VOD depends upon the explosive type and the density of the explosive core; the core density is influenced by the sheath material and processing method. To illustrate effect of sheath material on VOD, lead sheathed HNS MDF has a typical VOD of 6200 m/s, aluminum sheathed HNS MDF has a typical VOD of 6600 m/s and silver sheathed MDF has a typical VOD of 6900 m/s.

Coreload

The coreload is the weight of explosive contained in a given length of MDF; it is usually measured in grains per foot. Typical MDF coreload tolerance is 10% from a given nominal, but can be maintained to closer limits.

3. SELECTION AND APPLICATIONS

Selection of MDF must be based on the function to be performed, environments that will be experienced in service, weight, flexibility required, initiation sensitivity and available initiation stimulus. Usually, analysis of requirements for the overall system allows early selection of the explosive, coreload and diameter (or geometry) of the MDF required to perform the particular function. In many cases, MDF or MDF assembly designs are available that will satisfy new system requirements with little or no changes. General considerations in selecting MDF follow:

Energy Transmission

Low coreload MDF is used for transmission of explosive energy from a point of initiation to an output function with little or no disturbance imparted to adjacent components. End terminations with a gradual increase of explosive load are usually employed to intensify output for function of the next item and to accept initiation. Typical MDF explosive coreloads for energy transmission are 2 or 2.5 grains per foot; lower coreloads such as one grain per foot can be used to further decrease explosive load, weight and shock effects. For energy transmission, confined detonating fuse (CDF) is often employed. CDF is MDF in a confining structure designed to confine the explosive's detonation products so that they do not damage or contaminate adjacent components.

Timing

When precise timing is required for simultaneous or sequential events, VOD can be controlled to limits much closer than standard tolerances by special processing or hydrocompaction. VOD control of $\pm$ 20 meters per second has been achieved in many MDF configurations.

Initiation of MDF

MDF may be initiated either "end on" or through the sheath (perpendicular to the explosive core). End initiation is most common; through sheath initiation is used where geometry considerations preclude affixing the detonator to the end of the MDF. Each initiation fit-up requires careful control of alignment and spacing between the detonator and the explosive core of the MDF. Detonator to MDF interfaces are tested by Bruceton methods or similar to demonstrate that detonation will be transferred at the most adverse combination of tolerances.

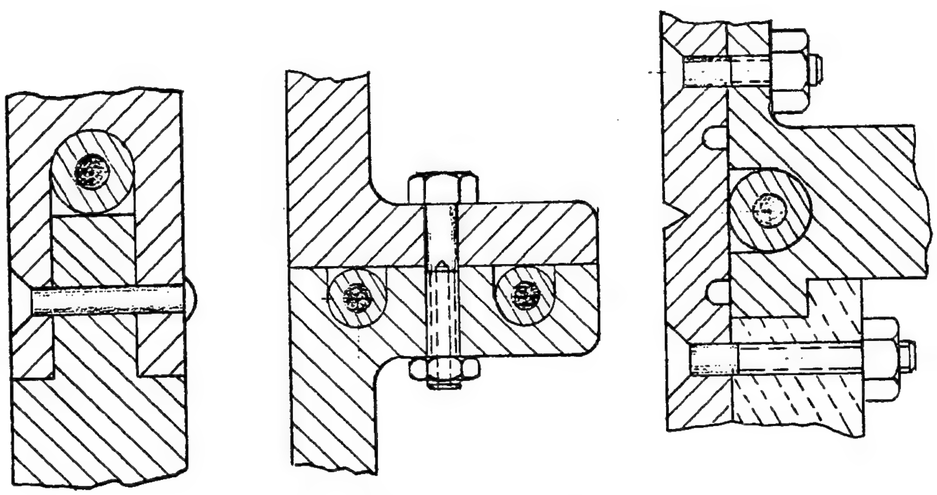
Number 6 strength or similar commercial blasting caps are used for MDF testing (per se) and for some systems applications. Special detonators or CDF assemblies are employed when systems requirements demand high no-fire levels (safety), thermal resistance, MIL-SPEC Qualification or other special consideration.

Initiation from MDF

MDF is used for functions such as initiation of multiple MDF energy transfer lines leading from a single manifold, initiation of percussion devices (by force applied to the primer) and initiation of pryotechnic materials. Each initiation fit-up requires control of alignment and spacing between the donor and the acceptor.

Severance

MDF provides rapid force application to accomplish severance for functions such as missile staging, port opening or multiple point mechanical release. Typical applications are sketched below:



MDF SEPARATION METHODS

When the explosion products must be contained, the MDF is encased in a flattened metal tube, elastromeric tube or bladder. Function of the MDF expands the tube or bladder applying force to the structure to be severed. When MDF is used for severance, the explosive coreload must be tailored to the structure that is to be severed and the structure must be designed to utilize the MDF explosive force effectively.

4. TYPES OF MDF

Ensign Bickford produces MDF in many configurations. The explosive, coreload, sheath thickness, sheath material, detonation velocity and geometry are variables that may be adjusted to meet exacting requirements within the basic limits of explosive performance and structural integrity of the sheath (and reinforcement materials if present).

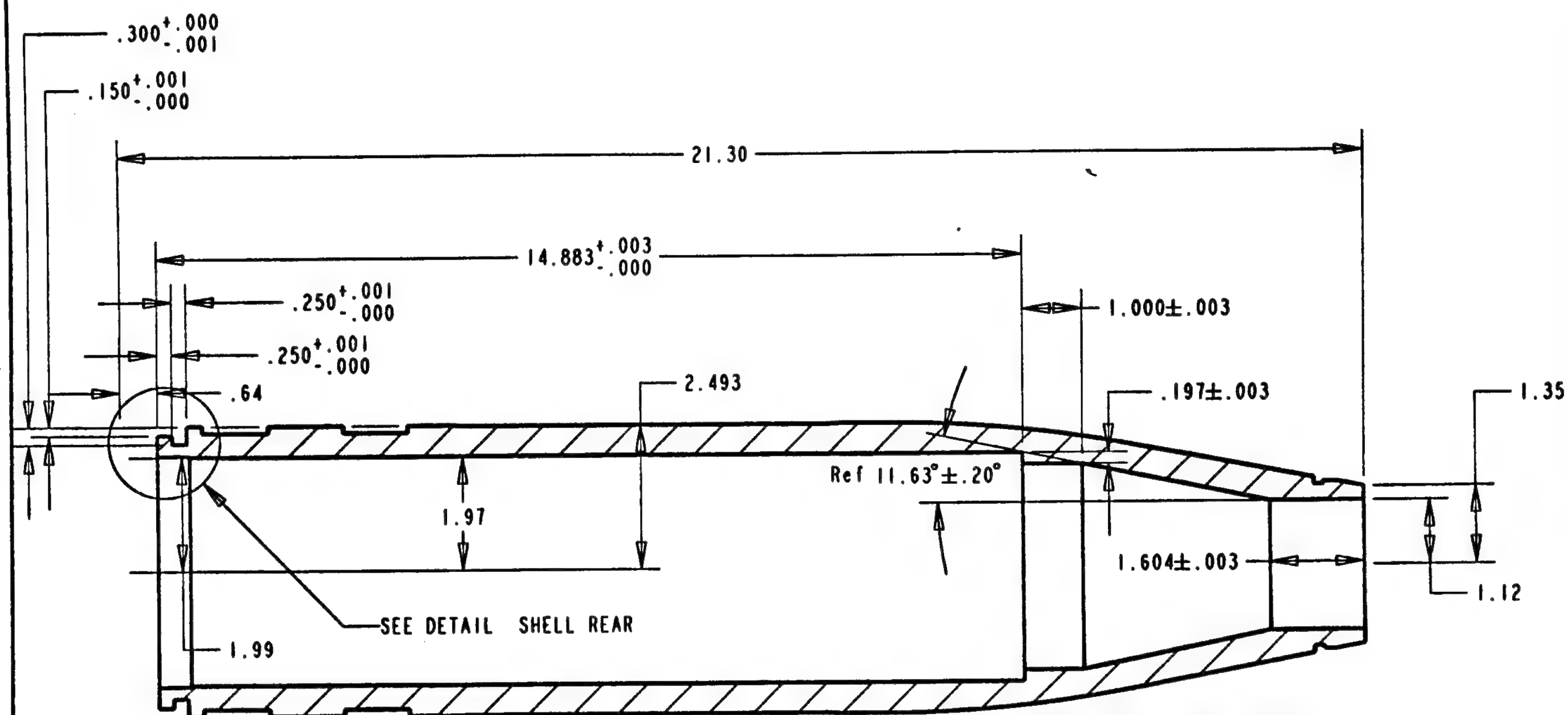
Standard MDF

The MDF tabulated here contains the explosives and coreloads most frequently used by the aerospace industry. MDF with special properties and specifications, is listed on the following pages. For further information contact the Aerospace Division.

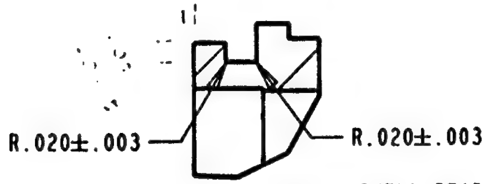
Coreload-Grain/FT + 10%	Diameter-Inch*	Sheath Material
1	.040 ± .002	Lead
1	.040 ± .002	Aluminum
2	.051 ± .002	Lead
2	.051 ± .002	Aluminum
2.5	.059 ± .002	Lead
2.5	.059 ± .002	Aluminum
2.5	.072 ± .002	Aluminum
5	.072 ± .003	Lead
5	.072 ± .003	Aluminum
10	.105 ± .003	Lead
10	.105 ± .003	Aluminum
15	.116 ± .003	Lead
15	.116 ± .003	Aluminum
20	.120 ± .003	Lead
20	.120 ± .003	Aluminum

*OD does not reflect extruded or reinforcing layers over the metal sheath.

Appendix F -Engineering Drawings of Modified Shell, Base, and Support Structures for the Fins and Obturator

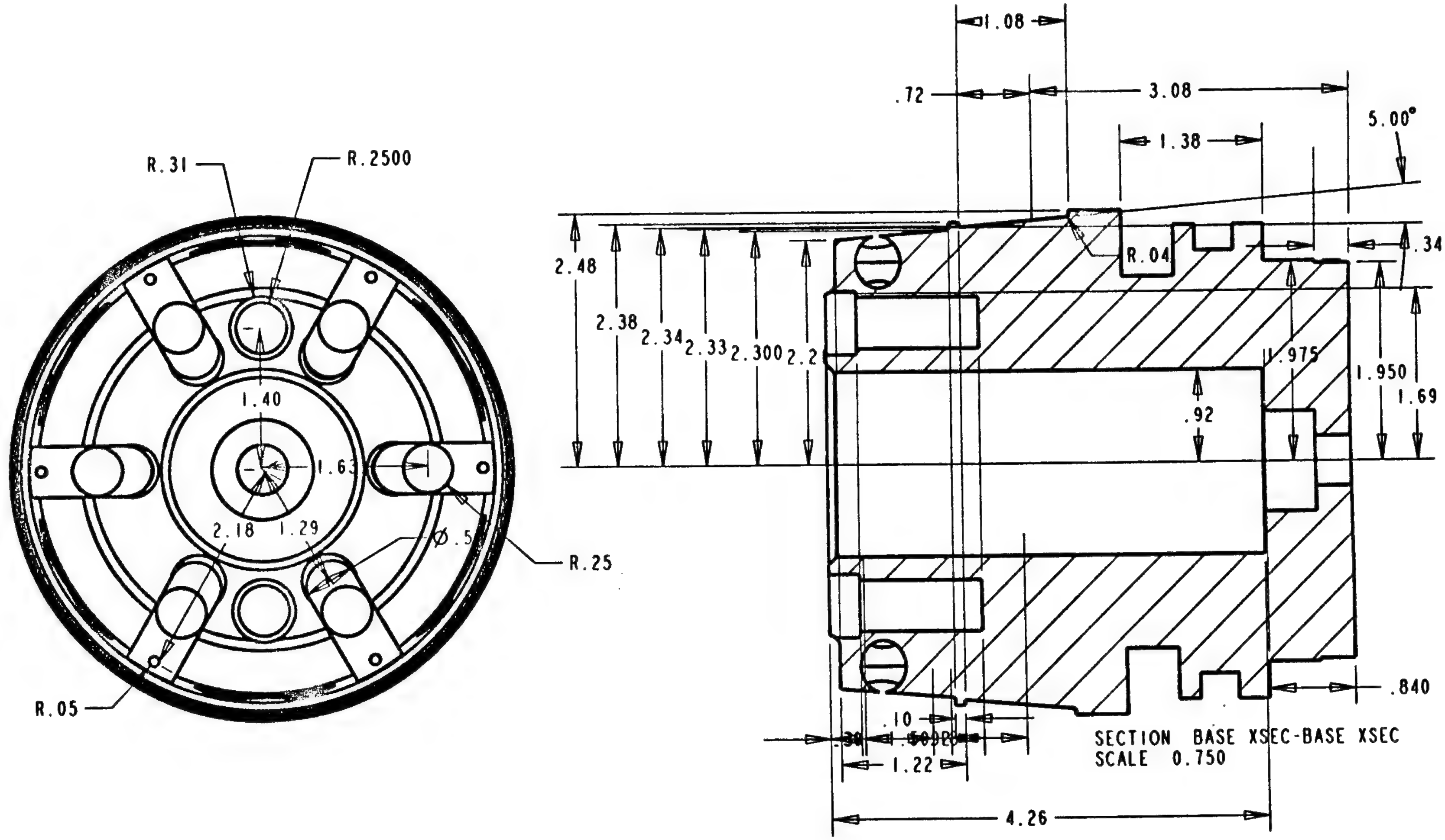


SECTION SHELL CROSS-SECTION-SHELL CROSS-SECTION
SCALE 0.400

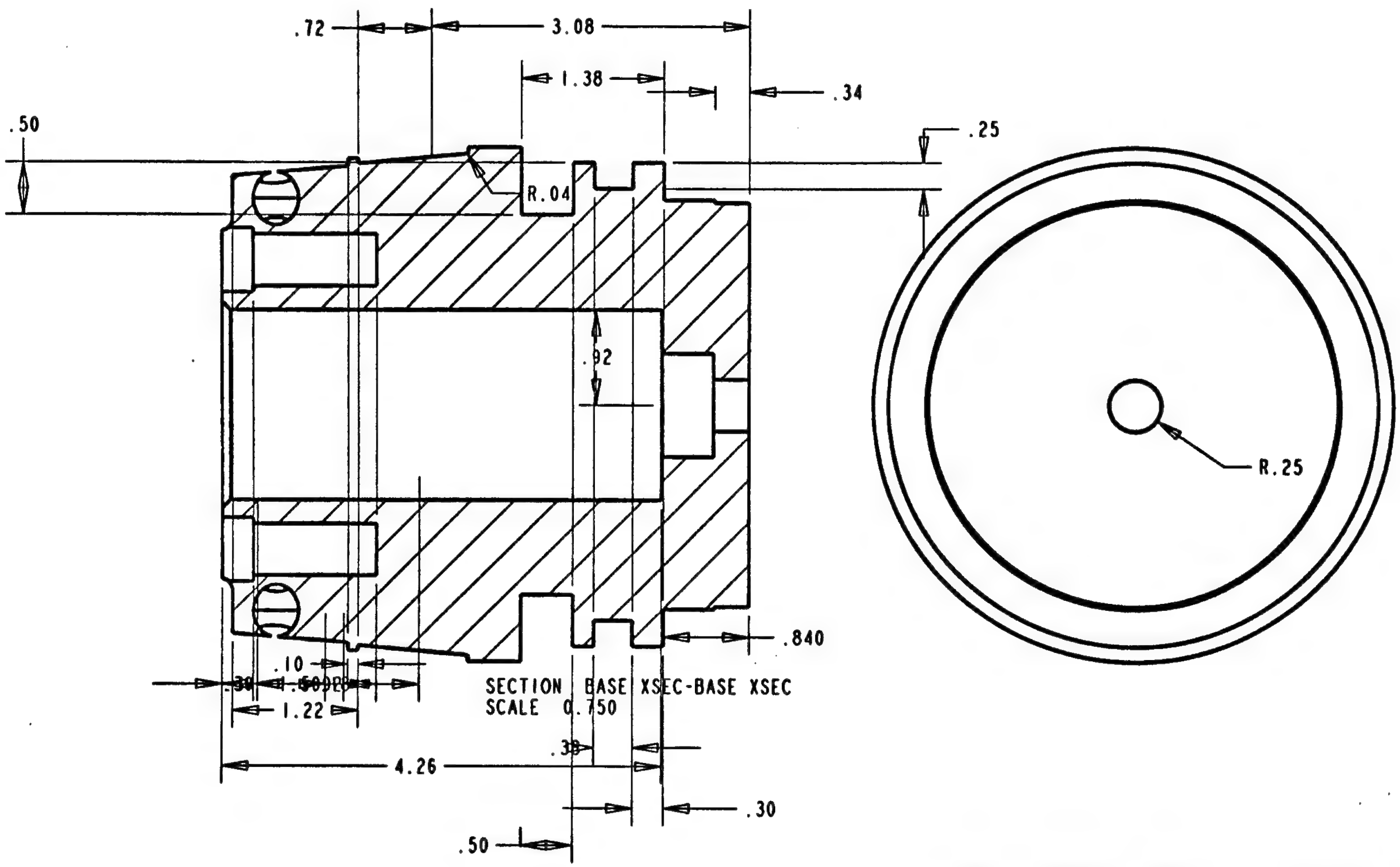


DETAIL SHELL REAR
SCALE 0.800

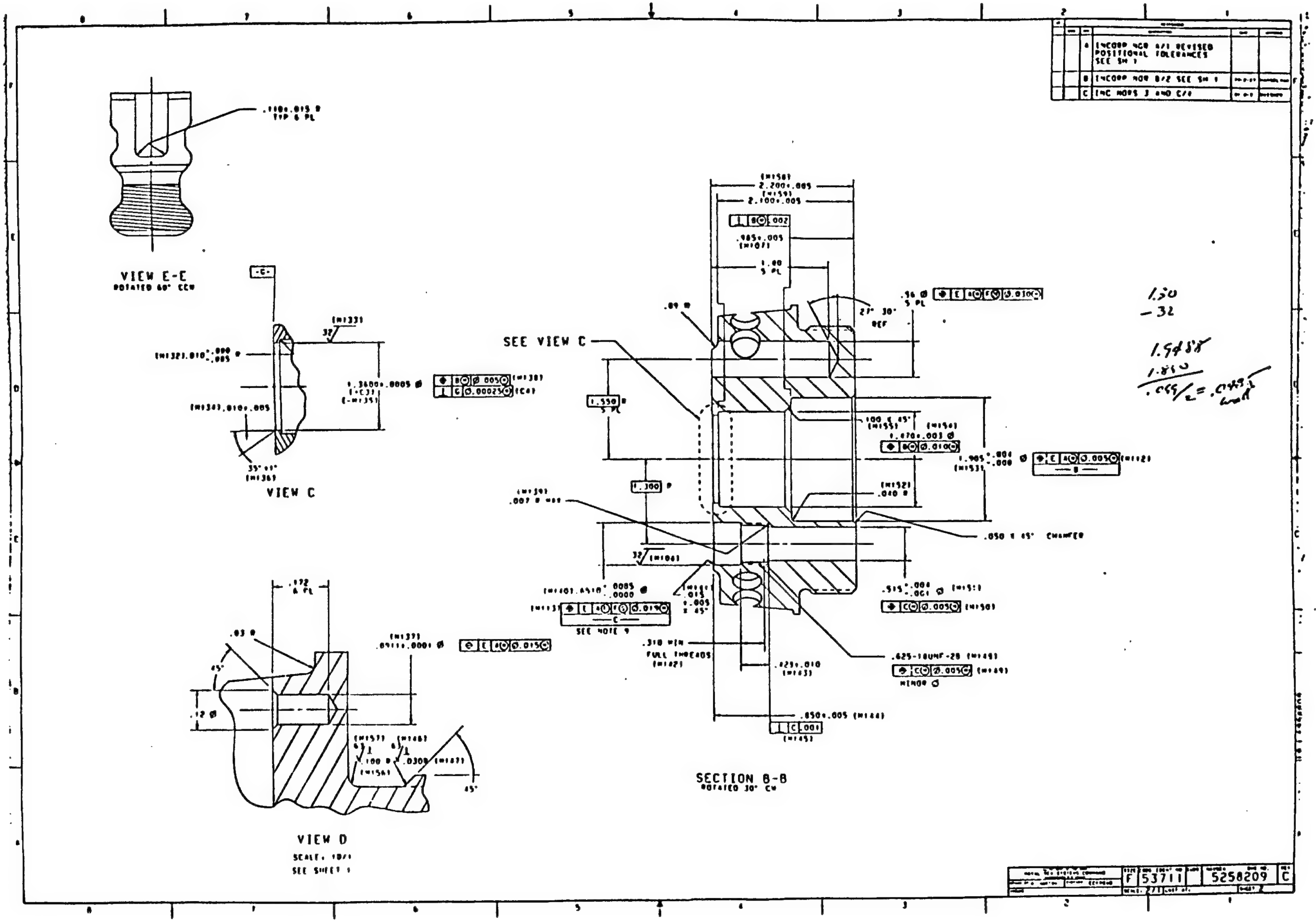
TOLERANCES All new tolerances noted. Dimensions w/out tolerances exist on current part.	WASP Shell		
	Prepared By: Garrett Shook		
	0.400	22-Feb-98	1381171
	SCALE	DATE	REF DRAWING



X.X ±0.1 X.XX ±0.01 X.XXX ±0.001	No detail to left of 3.8 inches	WASP Base Prepared By: Garrett Shook
	Scale	Date
	1.000	24-Feb-98



X.X ±0.1 X.XX ±0.01 X.XXX ±0.001	No detail to left of 3.8 inches	WASP Base Prepared By: Garrett Shook
	Scale	Date
	1.000	24-Feb-98

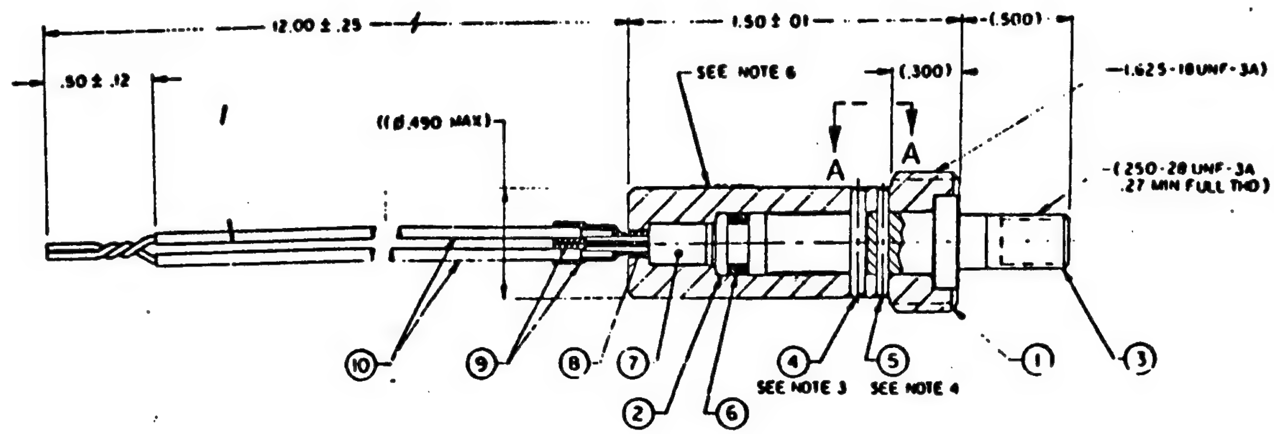


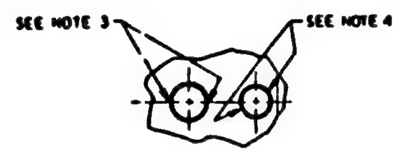
INCORP NOR A/1 REVISED POSITIONAL TOLERANCES SEE SH 1
INCORP NOR B/2 SEE SH 1
INC NORS 3 AND C/4
VIEW E-E
ROTATED 60° CCW
VIEW C
SEE VIEW C
SECTION B-B
ROTATED 30° CW
VIEW D
SCALE: 10/1
SEE SHEET 1
.050 X 45° CHAMFER
.625-18UNF-2B
MINOR Ø
.310 MIN
FULL THREADS
SEE NOTE 9
F 53711
5258209
C
1.30
-32
1.5488
1.850
.055/2 = .0475

Appendix G -Detailed Drawing of Bolt Thruster Designed by Special Devices, Incorporated.

NOTES: UNLESS OTHERWISE SPECIFIED.

1. BOND ITEM 7, SQUIB, INTO ITEM 1, HOUSING, WITH ITEM 8, EPOXY, AS SHOWN.
2. INSTALL ITEM 6, O-RING, ON ITEM 2, PISTON, AND SEAT INSIDE ITEM 1, HOUSING.
3. INSTALL ITEM 4, STOP PIN, SECURE BY STAKING IN PLACE OVER BOTH ENDS OF PIN.
4. INSTALL ITEM 3, EJECTOR, AND ITEM 5, SHEAR PIN. SECURE PIN IN PLACE BY STAKING OVER BOTH ENDS.
5. TERMINATE ITEM 10, WIRES, TO LEADS OF ITEM 7, SQUIB, USING ITEM 9, SOLDER SLEEVES. TRIM WIRES TO DIMENSIONS SHOWN, AND TWIST BARE ENDS TOGETHER TWO TURNS MINIMUM TO SHUNT.
6. LASER MARK PART NUMBER ON HOUSING APPROXIMATELY WHERE SHOWN.





VIEW A-A
SCALE: 10/1

10	AR	M22759/11-22-9	WIRE	MIL-W-22759/11
9	2	D-141-0103	SOLDER SLEEVE	
8	AR	2216 B/A	EPOXY	
7	1	104477-104	SQUIB ASSEMBLY	
6	1	2-007E515-80	O-RING	
5	1	108185	PIN, SHEAR	
4	1	108184	PIN, STOP	
3	1	108183	EJECTOR	
2	1	108182	PISTON	
1	1	108181	HOUSING	

SOI

THRUSTER, COVER REMOVAL

D | 14720 | 108180

Appendix H -Aerodynamic Properties of the SAL-GP Fins

Autopilot Parameters: Desired Bandwidth and Dam[illegible]ping Ratio: ωap = 3.0 Hz, εap = .7

ERGM Functional Flight Demo Aerodynami[illegible]ic Model Data (Short- No Rocket Motor Configuration)

Mach	Cdo	Cdc	Cdδ2	Cnα0	Cnαc	Cnα2	Cnδ	Cmα0	Cmαc	Cmα2	Cmδ	Cmq0	Cmqc	Clδt0	Clp0	Clα	Clα2
0.80	0.233	0.013	1.300	10.93	1.480	-13.46	1.180	-15.84	6.90	33.80	5.65	-158	-54.0	14.0	-25.0	-2.20	7.20
0.90	0.292	0.030	1.347	10.72	1.710	-9.52	1.280	-13.87	7.37	24.95	5.87	-179	-60.0	7.5	-17.5	-2.25	7.90
1.00	0.412	0.064	1.450	10.94	1.860	-8.50	1.350	-14.88	7.95	21.34	6.10	-160	-53.0	6.5	-14.5	-2.30	8.55
1.10	0.563	0.077	1.508	11.27	1.790	-10.50	1.290	-16.89	8.05	30.53	6.20	-134	-45.0	8.5	-19.0	-2.35	9.20
1.20	0.729	0.065	1.450	11.99	1.380	-14.40	1.330	-19.81	7.86	37.75	6.00	-265	-87.0	11.0	-23.2	-2.35	9.70
1.40	0.566	0.056	1.050	9.44	1.500	-5.23	1.130	-12.70	6.13	17.70	4.10	-200	-70.0	10.0	-21.0	-2.00	8.4[illegible]
1.60	0.483	0.050	0.814	7.84	1.370	0.00	1.060	-8.90	5.13	6.50	3.15	-152	-57.0	10.0	-20.5	-1.55	6.9[illegible]
1.80	0.432	0.046	0.646	6.68	1.280	4.20	1.000	-5.50	4.13	0.00	2.72	-130	-49.0	10.0	-20.5	-1.15	5.4[illegible]
2.00	0.400	0.044	0.512	5.90	1.120	7.70	0.940	-3.90	3.65	-4.50	2.36	-117	-41.0	10.0	-20.5	-1.10	4.5[illegible]
2.20	0.380	0.042	0.444	5.09	1.100	10.60	0.885	-2.30	3.39	-7.60	2.18	-106	-40.0	10.0	-20.5	-1.05	4.0[illegible]
2.40	0.362	0.041	0.407	4.27	1.026	13.10	0.855	-0.80	3.15	-10.00	1.98	-99	-37.0	10.0	-20.5	-1.00	3.5[illegible]

Aerodynamic Math Model

Note 1: All Moment Data are With Respect to a Refer[illegible]erence 23.35" From the Nose. Pitch and Yaw Channels are Symmetric.
Note 2: Unguided Configurations May be Modeled by[illegible]y Using Only Coefficients with "0" Subscripts (ex: Cd0, Cnα0, Cmα0)
Note 3: Coefficients with "c" Subscripts Denote Cana[illegible]rd Contributions (ex: Cdc, Cnαc, Cmαc)

Axial Force: Cd = Cd0 + Cdc + Cdδ2 * (δp [illegible] ^ 2 + δy ^ 2)

Pitch Normal Force: Cn = Cnδp * δp + (Cnα0 + C[illegible]nαc) * α + Cnα2 * α * | α |

Pitching Moment: Cm = Cmδp * δp + (Cmα0 + Cm[illegible]nαc) * α + Cmα2 * α * | α | + (Cmq0 + Cmqc) * (qd/2v)

Rolling Moment: Cl = Clδt0 * δt + Clp0 * (pd/2v) — [illegible] + [(δp*β - δy*α) / (Sqrt (2*δmax ^ 2)] * (Clα * αt + Clα2 * αt ^ 2)

Symbols: α = Pitch Angle of Attack, β = Yaw Angle [illegible] of Attack, αt = Total Angle of Attack, δt = Average Tailfin Cant (0.1 deg
δ = Pitch or Yaw Control Deflection (Subscripts "p" [illegible] and "y" Denote Pitch and Yaw, Respectively) - δmax = 10 degrees
V = Velocity , d = Reference Diameter , p = Roll Ra[illegible]ate, q = Pitching Rate

Mass Properties: Weight = 63.87 lbs @ 23.32" Fro[illegible]m Nose, Ix = .072 slugs-ft2, Iy = 1.187 slugs-ft2

Control Section: Canards Deployed on Estimated T[illegible]ime to Impact Generated by Onboard Software. ωc = 8.5 Hz, εc = .5

Autopilot Parameters: Desired Bandwidth and Dam[illegible]ping Ratio: ωap = 3.0 Hz, εap = .7

Motor Configuration)

Cmδ	Cmq0	Cmqc	Clδt0	Clp0	Clα	Clα2
.88	-722	-133	14.0	-25.0	-2.20	7.20
.25	-769	-160	7.5	-17.5	-2.25	7.90
.67	-737	-143	6.5	-14.5	-2.30	8.55
1.10	-678	-118	8.5	-19.0	-2.35	9.20
.62	-943	-409	11.0	-23.2	-2.35	9.70
.30	-645	-295	10.0	-21.0	-2.00	8.45
.73	-534	-175	10.0	-20.5	-1.55	6.85
.95	-480	-110	10.0	-20.5	-1.15	5.45
.31	-457	-73	10.0	-20.5	-1.10	4.50
.99	-430	-60	10.0	-20.5	-1.05	4.00
.65	-416	-33	10.0	-20.5	-1.00	3.50

Pitch and Yaw Channels are Symmetric.
n "0" Subscripts (ex: Cd0, Cnα0, Cmα0)
nαc, Cmαc)

:d0 * 0.95 for WSMR

Cmq0 + Cmqc) * (qd/2v)

ax ^ 2)] * (Clα * αt + Clα2 * αt ^ 2)

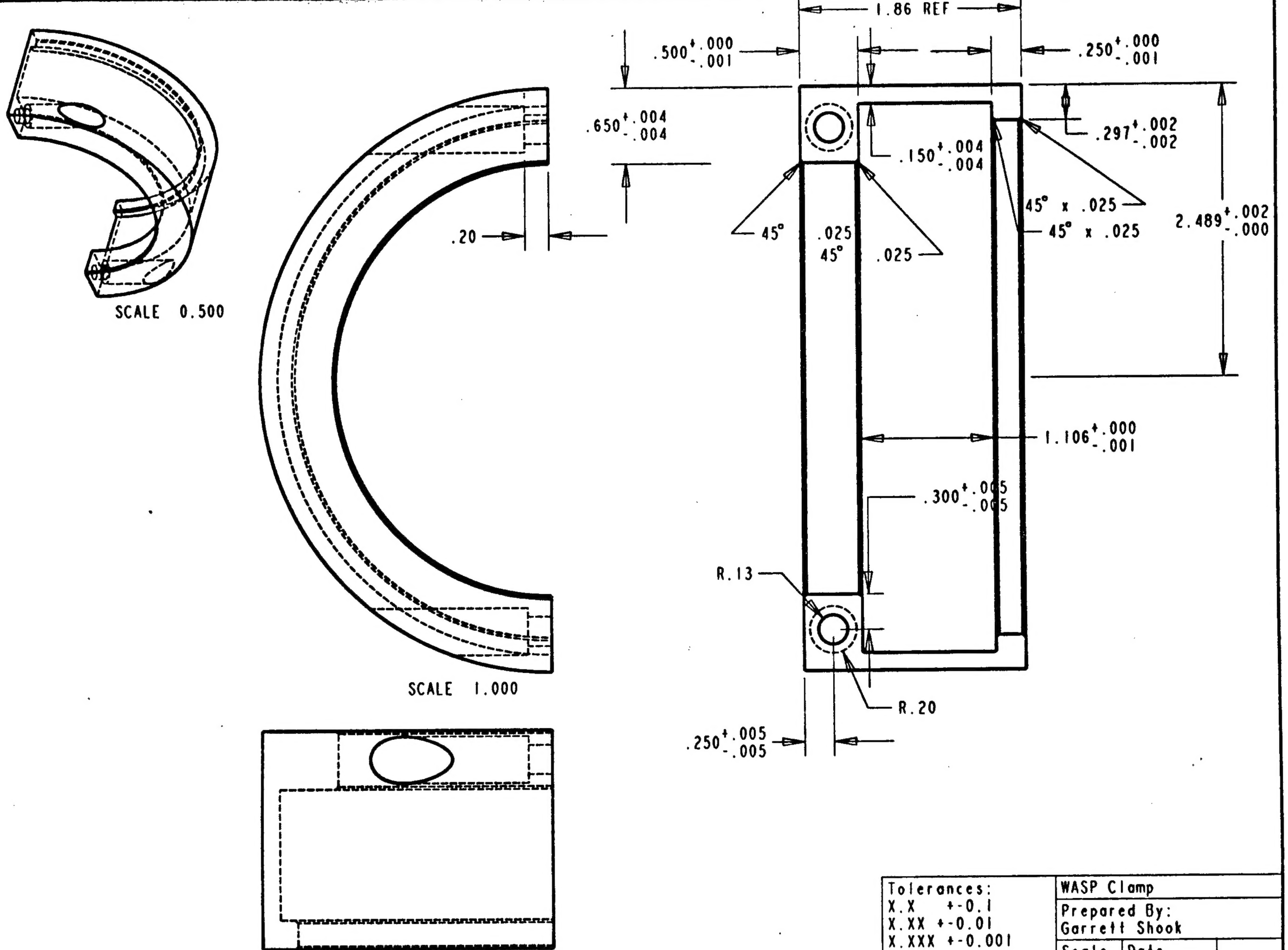
Attack, δt = Average Tailfin Cant (0.1deg)
; Respectively) - δmax = 10 degrees

ocket Burn. The Nominal Motor Ignition

ie, Ix = .118 slugs-ft2, Iy = 4.62 slugs-ft2
se, Ix = .095 slugs-ft2, Iy = 3.94 slugs-ft2

nboard Software. ωc = 8.5 Hz, εc = .5

Appendix I -Clamp Engineering and Manufacturing Drawings



Tolerances: X.X +-0.1 X.XX +-0.01 X.XXX +-0.001	WASP Clamp		
	Prepared By: Garrett Shook		
	Scale	Date	
Unless noted.	0.900	20-M· 98	